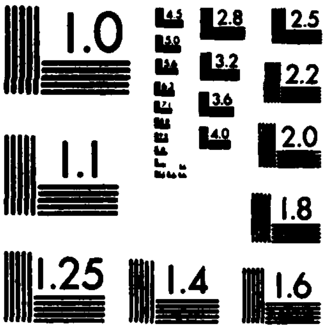
AD-A143 811 BURSTS AND PRESSURE FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS(U) IMPERIAL COLL OF SCIENCE AND TECHNOLOGY LONDON (ENGLAND) DEPT OF AERONAUTICS P BRADSHAW ET AL. APR 83 DAJA37-81-C-0162 1/1

UNCLASSIFIED F/G 20/4 NL


1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

(6)

AD-A143 811

Imperial College of Science and Technology

BURSTS AND PRESSURE FLUCTUATIONS IN
TURBULENT BOUNDARY LAYERS

FINAL TECHNICAL REPORT

by

P.Bradshaw and J.F.Morrison
Contract number: DAJA37-81-C-0162
R&D 3017-AN

Department of Aeronautics

84 08 02 038

BURSTS AND PRESSURE FLUCTUATIONS IN

TURBULENT BOUNDARY LAYERS

FINAL TECHNICAL REPORT

by

P.Bradshaw and J.F.Morrison

Contract number: DAJA37-81-C-0162
R&D 3017-AN

BURSTS AND PRESSURE FLUCTUATIONS IN TURBULENT BOUNDARY LAYERS

Final Technical Report

by

P.Bradshaw and J.F.Morrison

APRIL 1984

United States Army
EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY
London, England

Contract number: DAJA37-81-C-0162
R&D 3017-AN

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

REPORT DOCUMENTATION PAGE

BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A143 827	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Bursts and Pressure Fluctuations in Turbulent Boundary Layers		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) P Bradshaw and J. F. Morrison		8. CONTRACT OR GRANT NUMBER(s) DAJA37-81-C-0162
9. PERFORMING ORGANIZATION NAME AND ADDRESS Imperial College of Science & Technology Prince Consort Road, London SW7 2BY		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6.11.02A IT161102BH57-06
11. CONTROLLING OFFICE NAME AND ADDRESS USARDSG-UK Box 65 FPO NY 09510		12. REPORT DATE April, 1983
		13. NUMBER OF PAGES 42
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbulent Flow, Boundary Layers, Pressure Fluctuations

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Development of measurement techniques and acquisition of velocity- and pressure-fluctuation data in low-speed turbulent boundary layers are described. The object was to study the generation of pressure fluctuations by the turbulent eddies and to use the surface pressure fluctuation as a diagnostic tool, thus bringing together new and existing knowledge of the behaviour of the outer layer "large eddies", the inner layer and viscous sublayer, and the surface pressure fluctuations themselves. Data analysis is still in progress and this report is to be regarded as a fulfilment of contractual obligations rather than a

20. cont.

definitive presentation of scientific results.

Summary

Development of measurement techniques and acquisition of velocity- and pressure- fluctuation data in low-speed turbulent boundary layers are described. The object was to study the generation of pressure fluctuations by the turbulent eddies and to use the surface pressure fluctuation as a diagnostic tool, thus bringing together new and existing knowledge of the behaviour of the outer layer "large eddies", the inner layer and viscous sublayer, and the surface pressure fluctuations themselves. Data analysis is still in progress and this report is to be regarded as a fulfilment of contractual obligations rather than a definitive presentation of scientific results.

Keywords: Turbulent flow, Boundary layers, Pressure Fluctuations.

Contents

A. Introduction

This report outlines the methods used and the results obtained in experimental work in low-speed wind tunnels (typical stream speed $30ms^{-1}$). Surface pressure fluctuations below turbulent boundary layers were measured with commercial flush-diaphragm semiconductor-strain-gauge pressure transducers about 2 mm in effective diameter, and velocity fluctuations within the layer were measured with multiple hot-wire probes. Hot-wire configurations included four-wire arrays for measuring large-scale vorticity fluctuations, as well as more conventional probes for spatial correlation measurements. All fluctuating signals were recorded on analogue magnetic tape and all signal processing was done on a mainframe digital computer.

The object of the work was both to study the generation of pressure fluctuations within the turbulent flow and to use the surface pressure fluctuation as a simple diagnostic tool, or "footprint" of the large eddies, in conditional-sampling measurements. (Conditional sampling is a process in which statistical averages are accummulated only over the "interesting" periods of a fluctuating signal, for example periods of unusually intense activity in the signal being studied or in an associated diagnostic signal: for example the surface pressure fluctuation can be used to form an on-off "interesting/uninteresting" switch signal for conditional sampling of velocity fluctuations within the large eddies.)

The final set of data, taken with the latest designs of hot-wire rake and the final arrangement of backoff pressure transducer to reduce the effects of wind tunnel noise, was taken in the late summer of 1983, and analysis was held up

for some time by terminal malfunction of the digitizing system (now replaced). Final results are now being obtained, and samples are given below. These results will partly replace the older ones given in the present report. Therefore this report should be regarded as a fulfilment of contractual obligations rather than a definitive presentation of the results: the latter will be given in draft journal papers which will be sent to the project monitor in due course. However the results given here are believed to be reliable, though in some cases the pressure fluctuation signals are contaminated by background noise.

A pro al for extension of the contract, to allow measurements in adverse pressure gradient, has not so far been funded. However we ho e to carry out at least part of the proposed programme without renewed funding: the intention is to alter the ratio of outer-layer turbulence intensity to inner-layer intensity, so as to explore their relative contributions to the surface pressure fluctuation. This will provide a test of the hypotheses about turbulence structure and the generation of pressure fluctuations which are being formulated on the basis of our existing data.

B. Progress in 1981-82 - Equipment and Techniques

1. Work done to date

As mentioned in the first periodic report, the chosen research assistant was not able to start work until 22 June 1981, but the program outlined for Year 1 in the Contract proposal is now nearing completion. Assistance with instrumentation was given by a second research assistant, recruited on a temporary appointment for eight weeks in the summer of 1981.

Since the use of wall pressure signatures to detect turbulent bursts will eventually require the analysis of simultaneous signals from several transducers, we had hoped to be able to use the cheaper submerged-diaphragm "pin-hole" microphones, rather than small-diameter flush-mounting pressure transducers. We therefore purchased one "pin-hole" device for evaluation and comparison with the more expensive flush diaphragm type. Frequency spectrum measurements confirm the finding of Bull and Thomas (Physics of Fluids,vol 19, p.597, 1976) that the frequency response (or spatial resolution) of the pin-hole type of microphone is very much poorer than would be expected from the diameter of the pin-hole. Therefore, we do not expect to be able to use the pin-hole microphone for serious work, although it is perfectly adequate for low frequency measurements and has been helpful in checking that none of the spurious low frequency peaks found in the spectra were attributable to mechanical vibration of the flush-diaphragm transducer. When our own work is slightly more advanced, we propose to write a note on the response of the pin-hole microphone, to support the published conclusions of Bull and Thomas. Therefore, we do not regard the expenditure of time and money on assessing the pin-hole pressure transducer as having been entirely wasted.

As mentioned in the first six-monthly report, considerable trouble with electrical pick-up was experienced in the early stages but this has been satisfactorily eliminated by the use of CIL type 113 strain gauge amplifiers, which have sophisticated

common mode rejection circuits, low noise, and various other features which make them ideal for the present work.

We have made measurements of pressure fluctuations below turbulent boundary layers in three of the Department's wind tunnels, two 30" x 5" blower tunnels (one with a lightly built wooden working section and the other with a working section floor consisting of a ½" aluminium plate) and the Department's 3' x 3' low turbulence tunnel. This has permitted positive identification of low frequency spectrum peaks due to "organ pipe" resonances in the wind tunnels: such resonances, and also pressure fluctuations at the drive motor shaft frequency or the blade-passing frequency, are inevitable, although they can be reduced by special acoustical treatment. The contribution of these acoustic and vibration signals to velocity fluctuations measured with hot wires is very small, and they will therefore not appear in any pressure-velocity correlation measurements, while it is easy to subtract the measured energy contributions of the spectrum peaks from the overall mean square pressure fluctuations. The only significant difficulty caused by these spurious fluctuations is that they complicate the "eyeball" interpretation of pressure traces below turbulent bursts. However, since the spurious fluctuations are almost perfectly correlated across the cross sectional width of the tunnel, it is possible to mount another pressure transducer in a non-turbulent part of the stream and subtract its signal from that of the boundary layer transducer so that a "clean" trace can be observed.

Apart from the aforementioned spurious spectrum peak, the frequency spectrum measured in all three wind tunnels, at different tunnel speeds and with different thicknesses of boundary layer, collapsed very well together, and we therefore believe that our transducers, electronics, and pressure fluctuation measurement techniques are satisfactory.

Simultaneous measurements with the surface pressure fluctuation transducer and with a multiple-hot-wire array are now in progress. Data have so far been taken with

(i) a "rake" of eight hot wires measuring the horizontal velocity component at different vertical positions in the boundary layer

(ii) a four wire probe array which can measure the rate of strain and vorticity in the x y plane, $\partial v/\partial x \pm \partial u/\partial y$, at one distance from the surface at a time

(iii) "pattern recognition" analysis of the simultaneous velocity and pressure traces is now in progress.

It should be pointed out that the "vorticity probe" measures only the large scale part of the vorticity with a spatial resolution depending on the distance between the two single wire probes used to measure $\partial u/\partial y$ and on the time interval Δt used in making $\partial v/\partial x \simeq (v(t + \Delta t) - v(t - \Delta t)) / (2U\Delta t)$. We have arranged that the resolution in the two directions shall be equal: this, of course, selects only an arbitrary part of a rapidly rising spectrum, but the rate of strain and vorticity fluctuations appear in the forcing function for the Poisson equation for pressure fluctuations (as shown by Bradshaw and Koh, Phys. Fluids 24, 777, 1981) and integration of the Poisson equation to obtain the pressure fluctuation at a distance point produces a strong spectral cut-off, so that the wave-number-limited measurements of vorticity and strain-rate fluctuations are a meaningful measure of the contribution of outer layer bursts to the surface pressure fluctuation.

2. Plans for second year of Contract

The data which have now been acquired are being used for two of the objects outlined in the original proposal, first, eduction of inner layer bursts from the measured velocity fluctuation field, and, secondly, an investigation of the correlations between features of the surface pressure fluctuation pattern and the occurrence of bursts: indeed, the data also provide a first cut at the problem of the relation between the outer irrotational motion and the surface pressure fluctuations. We propose to analyse the data already acquired fairly extensively, but in the realization that the analysis will suggest further measurements even if the existing data are intrinsically satisfactory. Therefore, we anticipate that the second year of the contract will be taken up almost entirely by the analysis of the existing data and the acquisition and analysis of further data as suggested by the preliminary work. We are ahead of schedule in the sense that the acquisition of outer layer data planned for year 2 (section 4 of the original proposal) has already started, and behind schedule in the sense that we have not yet fully verified that the presence of turbulent bursts can be sensed by using pattern recognition techniques on the uv signal: however, we anticipate that the burst recognition technique used by other workers will be satisfactory for preliminary purposes, although our own data analysis will probably suggest refinements.

As indicated above, we plan a short note on the response characteristics of the "pin-hole" pressure transducers, but at present we do not anticipate producing a formal paper on the main part of the pressure fluctuation work during year 2 of the Contract.

C. Progress in 1982-83 - Preliminary measurements in two wind tunnels

1. Work done to date

At the end of the first year of the contract, in February 1982, we reported that pressure-fluctuation measurement techniques had been developed, that measurements had been made in three of the Department's wind tunnels to test their suitability for the main experimental programme, and that serious data acquisition using multiple hot-wire arrays and surface pressure transducers was in progress.

In August 1982 we reported analysis of the preliminary data taken in the small (30 in x 5 in) blower tunnel, and commencement of detailed data acquisition in the 3 ft x 3 ft tunnel. The blower tunnel results have now been written up as an internal Department Technical Note , principally as a record of contributions made to the work by Mr. Y.Z. Bian, an academic visitor from the People's Republic of China. Mr. Bian provided useful assistance in the early stages of the project, at no cost to Contract funds: he has now returned to China and, as we specified in previous reports, he has not had access to the main set of data.

During the period August 1982 - February 1983, the majority of time has been spent analysing data gathered in the Department's 3 ft x 3 ft tunnel. The large working section provides an opportunity for development of a thick boundary layer giving improved wire resolution and good signal-to-noise ratio for the pressure transducers. It also ensures minimal interference of the roof boundary layer with potential flow measurements taken above the floor boundary layer. The signals from the pressure transducers were "backed off" by subtracting that of a dummy transducer rigidly mounted in the free stream in order to remove low frequency contributions caused by vibration and acoustic resonances.

Three hot-wire rake configurations have been used so far, in conjunction with a wall pressure transducer and wall-shear stress wire mounted immediately below the hot-wire array. The arrays used were (a) a vorticity array, (b) a rake of u-wires and (c) a rake of

x-wires. The vorticity array was designed to measure fluctuating shear stress, rate of strain, $\partial v/\partial x + \partial u/\partial y$, and vorticity, $\partial v/\partial x - \partial u/\partial y$, in the x-y plane, thus permitting evaluation of the source terms in the pressure fluctuation equation. It consisted of a cross-wire probe, with single wires 1.5 mm above and below. The resolution of such an array is currently being checked independently as part of the SERC-supported work on conditional sampling of the large-scale structure. It is thought that the resolution will be sufficiently good to provide meaningful wave-number-limited measurements of the strain-rate and vorticity fluctuations, but techniques for making sub-miniature hot wire probes with a wire length less than a tenth of that used here, i.e. 1 mm, are now being developed - again at no cost to the contract - by Dr. P.M. Ligrani, a research fellow supported by SERC. The U-wire array has been used to provide pressure-velocity correlations in and above the boundary layer to extend the measurements of Willmarth and Wooldridge (1963) and to check the predictions of Mulhearn (1975) for the part of the pressure fluctuation produced by an interaction between the turbulence and the mean flow. The x-wire array has been used to follow inner layer burst development via conditional pressure-velocity correlations.

Several conditional sampling programs have been developed in order to educe regions of high turbulent activity using the Variable Interval Time Averaging (VITA) algorithm of Blackwelder and Kaplan (1976) . They are all modular, both in conception and form, so that the detection algorithm can be applied to any of the input signals. The algorithm has been extended to include a quadrant analysis if the detection signal is the uv signature, and positive/ negative gradient decisions if the temperature signal is used. Use of temperature discrimination downstream of a spanwise line source of heat on the surface for determination of intermittency provides a link to the outer-layer work mentioned above.

Temporal resolution of the data is limited by the frequency response of the available recording equipment (40 kHz); estimates of the Kolmogorov timescale are of the same order as the sampling interval. The smallest event physically realisable is the Kolmogorov length scale although resolution is further limited by sensor size. The short-time averaging period of the algorithm has been set to a time comparable with the time scales resolvable by a 1 mm hot-wire (usually 5-10 times the sampling interval). Thus the VITA algorithm is essentially immune from "dropouts" (short irrotational regions, either physically or mathematically produced, within a region of significant turbulence). The detection signal primarily used is the uv signature; it is an obvious choice when one wishes to detect motions that are principally involved in the production of shear stress.

Analysis of the data provided by the vorticity array in the inner layer ($y/\delta = 0.114$) is shown in figures (1) to (3). Ensemble averaged time histories for u-positive (sweeps) and u-negative (ejections) are shown in figures (1) and (2) respectively. The threshold can be optimised by reference to identity traces and visual comparison with the instantaneous detection signal. The data of these figures are from a total sample length of 2.4 seconds of real time. The ensemble-averaged time histories possess the relevant features attributed to ejection and sweep phenomena visually observed during a burst, but we have not yet tried to establish a direct correspondence between events detected here and visually observed near-wall motions, preferring to wait until a vorticity sensor with better spatial resolution is available. The behaviour of the wall pressure signature corroborates the data of Thomas (1978) and shows that the wall pressure is not of the correct character to play a causal role in burst production: the signature appears to be the result, rather than the cause, of the burst.

Figure (3) summarizes the statistics of burst occurrences in the form of probability distribution functions (pdf), as suggested by Murlis et al (1982) . Distributions on the left show pdf's of (a) sweeps and (b) ejections. Their tendency to be bi-modal is spurious

and no more than an artifact of the sampling algorithm: the minor peak is at the short time averaging period. The pdf's of u and v at event times show that ejections are mainly of larger amplitude and that the distribution of velocities during sweeps is broader.

Figure (4) shows conventional pressure-velocity correlations for $0 < y/\delta < 1.15$. The pressure signal has been digitally filtered in order to assess the effect of spurious low-frequency contributions.

The data obtained to date has been found to be deficient in two respects. Firstly the "back-off" transducer needs to have the same sensitivity to vibration as the wall sensors in order to obtain reliable wall-pressure spectra at low wave-numbers. Thus a further flush-mounted transducer is being purchased for this purpose. Secondly the wall shear stress data is not likely to be satisfactory in the present data set because of the parasitic effects of the wall on the heated wire placed in the boundary layer sublayer. A gauge specifically designed to give reliable signals proportional to the time-dependent wall shear stress is currently being tested. A second wire or film operated at a higher overheat ratio than the sensor is placed directly behind or beneath it in order to act as a heat guard. This idea was suggested by Ajagu, Libby and La Rue (1982) and the gauge is being assessed with particular regard to the optimum combination of overheat ratios, the relative positioning of the guard and sensor, and the limits to size of fluctuation that can be reliably estimated.

2. Future Work

When the wall shear stress gauge has been fully assessed, a final set of data will be obtained. Wall shear stress data is of particular importance for the study of outer/inner layer interactions

and benefits from not being so susceptible to randomness of phase that plagues conditional averages, particularly those from signatures of sensors at large distances from the wall. Data already obtained will be checked with some improvements in wire positioning relative to the wall. Also two other configurations will be used. One is to provide data on the effect of outer layer intermittency on inner layer events (and vice-versa): i.e. temperature-conditioned measurements in the outer layer can be correlated with shear stress conditioned measurements in the inner layer. Two-point conditional correlations or joint-pdf's ought to provide quantitative information. Also the correlation of the irrotational motion above the boundary layer with the wall pressure will be supplemented by correlations between the potential flow and the source terms of the pressure-fluctuation equation.

It is hoped to include a phase-jitter algorithm in any conditional analyses to minimise the effects of phase jitter. This should make interpretation of conditional averages triggered by signatures of sensors at large separations more reliable.

During the final year of the contract, we expect to produce several draft journal papers on the work.

IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF AERONAUTICS

Prince Consort Road, London, SW7 2BY

I.C. Aero TN 82-107 November 1982

Measurement of the correlation between the fluctuating wall pressure and the fluctuating longitudinal velocity in a turbulent boundary layer

by

Y.Z. Bian, J.F. Morrison and P.Bradshaw

Summary

Measurements of the space-time correlation between the fluctuating wall pressure and the fluctuating velocity in a turbulent boundary layer with zero longitudinal pressure gradient are reported.

The structure of the pressure-velocity correlation was obtained from measurements of the space-time correlation between the fluctuating wall pressure and the fluctuating velocity at various distances in x-direction and various points in y-direction in the boundary layer. The largest variations of pressure-velocity correlation with x-direction and y-direction distances from the pressure transducer are near the pressure transducer.

The bursting phenomenon can be qualitatively observed from the traces of simultaneous records of the fluctuating wall pressure and the fluctuating velocity signals.

D. Progress in 1983-84 - Final results and data analysis

1. <u>Work done in final year of contract.</u>

The previous data set, obtained in the 3 ft x 3 ft wind tunnel in August 1982, has been completely analysed. For these tests a single x-wire hot wire probe, measuring u and v component fluctuations, was mounted vertically above a wall-shear sensor and a wall pressure fluctuation transducer. Preliminary results were given in the second annual report (February 1983): we have now made an extensive analysis of the sensor signals during "events" (including both "bursts" in which there is a vigorous movement of fluid away from the wall, and "sweeps" in which fluid moves towards the wall). Attention has been concentrated on the inner layer, and considerable effort has been devoted to developing a reliable algorithm for "event" detection, based on the variable interval time averaging (VITA) sampling algorithm developed at University of Southern California (see Appendix). Ensemble average signal traces and probability distributions at event times have been generated. The probability distributions indicate that the VITA technique preferentially detects events of about the same length as the short time VITA averaging period, and that, during these events, excursions in uv can be an order of magnitude larger than the long time mean. These data provide a first view of the temporal relationship between log region events and wall signatures, one of the main aims set out in the original proposal.

Analysis of conventional space-time wall-pressure and wall-shear correlations with hot-wire signals at various positions across the whole boundary layer and above it has yet to be completed. (The object of this analysis is to establish the relationships between inner-layer events and the large eddies in the outer layer, another of the main aims of the original proposal.) Correlations with irrotational fluctuations above the boundary layer extend previous measurements, and will also act as

a check on the "backoff" pressure transducer, rigidly mounted in the free stream in order to detect pressure fluctuations generated by the wind tunnel, which can then be subtracted from the wall-pressure measurements. Genuine free stream fluctuations and their spatial correlations are being compared with the theory of Phillips and the recent extensions of it by Wood and Ferziger in this Department.

A four-wire array, capable of measuring the instantaneous rate of strain in the x-y plane and the z-component of vorticity, has been used in conjunction with a wall-pressure transducer to investigate the relation between large-eddy structure and wall-pressure fluctuations using both conventional and conditional correlations. More definitive results will be acquired later.

A new set of data in the 3 ft x 3 ft tunnel has been gathered. The measurements are essentially repeats of previous ones taken with wall transducers and single hot wire probes, but data have also been taken with a "rake" of x-wire hot wire probes vertically above the wall sensors, to detect large-eddy development. A rake specifically designed to show the inner/outer layer relationship was also used. Analysis involves the two-point sampling scheme in which the "burst"-detector hot-wire probe placed in the logarithmic region can detect the two types of event, which can be correlated with the outer, large-scale, intermittency.

As mentioned in the 1982-83 Annual Report, a hot-wire surface shear stress meter, with a hot film on the surface immediately below it to act as a "guard ring" as suggested by Ajagu, Libby and LaRue, has been tested. Unfortunately the main advantage of the probe as demonstrated by those authors, namely coincidence of the calibration in laminar and in turbulent flow, was not achieved in our own experiments, and we have abandoned the technique after expending an embarrassingly large amount of effort on it. (Possible reasons for the disagreements of the two

sets of results are now being investigated by Professor LaRue.) We are now using a conventional hot wire probe placed very close to the surface to measure surface shear stress. Professor Ligrani's miniature hot wire probes (also mentioned in the 1982-83 Annual Report) are now being used to measure wall shear stress fluctuations, and will provide useful checks on the present measurements as well as their main purpose of greatly improving spatial resolution (not too critical for our own work).

The final six months of the contract have been spent in the analysis of the new 3ft x 3ft tunnel data set, in some further analysis of previous data, and in acquisition of final check data.

2. Conclusions

We feel that we have achieved the main aims set out in the original proposal, namely, to investigate the behaviour of bursts in the inner region of turbulent boundary layers, and the relation of bursts to (i) surface pressure fluctuations (ii) the large eddies in the outer intermittent region. However, all the measurements have been done in boundary layers in zero pressure gradient over a necessarily small range of Reynolds numbers, so that the ratio of typical inner-layer intensities and length scales to typical outer-layer scales has remained fixed. Generalization of the results that we have obtained, and tests of our hypotheses on inner-layer behaviour, require either tests at a very different Reynolds number or tests in an adverse pressure gradient where the outer-layer intensity is greater and its influence on the inner layer is larger. Large changes in Reynolds number are difficult to arrange in pressure-fluctuation experiments, unless different pressure transducers are used for different speed ranges. Unfortunately our proposal for one further year's work on the contract, on bursts and pressure

fluctuations in turbulent boundary layers in adverse pressure gradients, was not accepted. We still feel strongly that this work needs to be done before our deductions from our existing results can be regarded as generally trustworthy, rather than as post hoc explanations of measurements in only one flow. Therefore we are supporting this work from our own resources, and propose to delay final writing up of our results and deductions until the check measurements in pressure gradient are available. As stated in the Summary, this report is to be regarded as a progress report and a fulfilment of the contractual obligation to produce a "final" report two months after the end of the contract, rather than a complete presentation of data and conclusions.

E. Final Experimental Arrangement and and Overview of Data

All the final experimental data come from measurements taken in the Department's 3' x 3' wind tunnel. This has the advantage of a large working section which allows measurements in the free stream (turbulence intensity < .05 percent) to be made without interference from the boundary layer on the opposite wall. The tunnel is also relatively insensitive to vibration.

The constant-pressure boundary layer was tripped by a 6" long strip of coarse sand paper which also served as electrical and thermal insulation for 26 s.w.g. Nichrome wire used for heating to denote the turbulent/non-turbulent interface. For an input of 1.3 kW the increase in mean temperature of the boundary layer above the free stream was about 1^oC where $\delta \approx 3"$. Otherwise conditions were very similar to those of Andreopoulos and Bradshaw (1980) who used the same tunnel but not the floor. The present measurements were carried out at $Re_\theta = 1.46 \times 10^4$, $U_e = 32.26\ ms^{-1}$ and $\delta_{995} = 64.39$ mm at which $u_\tau = 1.11\ ms^{-1}$.

The pressure transducers used are flush-mounted and of strain-gauge/semiconductor plus diaphragm type (0-2 psi). These have a slightly non-linear response near zero pressure which was avoided by simple biasing. Purpose-built chips were used to drive and amplify the transducer output; for an amplifier gain of about 100, the bandwidth was about 30 kHz. Thus the resolution of these transducers was limited only by diaphragm size. The outer diameter of the transducers is 2.3 mm although internal dimensions and allowance for an inflexible rim to the edge of the diaphragm reduce this to about 1.5 mm ($d^+ \approx 10^6$).

In order to achieve better spatial resolution, a pinhole type transducer ($d = 0.8$ mm) was tried but the resonance occurred at 1.25 kHz and higher frequencies were therefore attenuated. Further work is required in this area to clarify the effect noted by Bull and Thomas (1976) where the spectral density measured with a pinhole transducer at higher frequencies was larger than that measured by a flush-mounted transducer of the same non-dimensional size. Goldman and Chung (1982) specify $d^+ = 40$ as a limit at which the non-dimensional acoustic impedance approaches a minimum limiting value. Thus the effect noted by Bull and Thomas for their transducer ($d^+ = 45$) is likely to be caused by a change in the response kernel associated with the surface discontinuity of the pinhole.

The resolution of the present transducers is good enough to resolve pressure-producing disturbances of order $\ell^+ \simeq 100$; resolution down to $\ell^+ = 30$ is possible by changing the flow parameters and assuming that similarity variables of the form $\omega \underline{x}/U_e$ are sufficient to collapse the cross-spectral density of two wall pressure signals (even at small $\underline{x} << \delta$) for different flow conditions. This would be beneficial for a study of wall pressure correlations specifically at small separations or for correlations with velocities measured with miniature wires. Present wire lengths are ~ 1 mm.

All wall pressure signals in this study were "backed-off" by that from a transducer rigidly mounted in the free stream to monitor diffuser-induced disturbances, vibration and acoustic ("organ-pipe") resonances. An analogue spectrum is shown in figure 5a. This shows a region in which $\phi(\omega) \sim \omega^2$ as predicted by Bradshaw (1967a) for low wave numbers. In fact, this region is not repeatable as shown by subsequent spectra, figure 5b. The discrepancy can be attributed to sound waves; in the present case nearly all the harmonics are subtracted by the back-off with the exception of those with wavelengths less than the streamwise separation of the wall and back-off transducers (~ 0.5 m). The

foregoing implies that the sound waves are uniformly correlated over the cross-section of the tunnel. A more important cause of low-frequency variations in the spectra can be attributed to manufacturing imperfections on the face of the transducer. The outer rim of the transducer could cause a ridge or cavity of size $h/d \simeq 0.1$ - well outside Gaudet's (1978) criteria for transducer misalignment.

All the spectra obtained showed a definite ω^{-1} range as predicted by Bradshaw (1967b). There is also a region of $\omega^{-7/2}$ - a slightly steeper gradient than $\omega^{-7/3}$, as predicted by Monin and Yaglom (1975), due to transducer resolution. The lower frequency end of the $\omega^{-7/3}$ dependent range, at which transducer resolution errors become apparent, corresponds to the lower limit of the inertial subrange. Estimates for the minimum value of Re_λ required for the existence of an inertial subrange vary from about 50 → 100. For the present case $Re_\lambda = 62$ at $y^+ = 100$ which not only confirms the expected existence of the inertial subrange, but also confirms the resolution properties of the transducers.

Various combinations of arrays of hot wires (X-wires) and temperature ('cold') wires were used mounted with various streamwise and spanwise separations from the wall pressure transducers. A wall shear stress wire (a single hot-wire run at an overheat ratio of 1.3) was also mounted immediately behind the downstream pressure transducer, at $y^+ = 3.5$, $y/d = 10$. For $y^+ < 5$, the signal is proportional to the wall shear stress. The wire was mounted on a plastic plug to minimise heat losses and calibrated in situ against a Preston tube. It is possible to correct the degraded frequency response analytically as done by Bellhouse and Schultz (1968).

All velocities were corrected for the effect of temperature fluctuations on the hot wires in the heated boundary layer. The wall pressure transducers are quite sensitive to temperature

fluctuations although spectra in the heated flow agreed very well with those in the unheated flow.

Data Summary.

All wire measurements were obtained with a 16-port rake. Each port is capable of holding combinations of velocity and temperature wires and is spaced nominally at 5 mm intervals. This rake was especially convenient for vorticity/strain-rate arrays. Each wire assembly was used with a fixed combination of wall sensors: two pressure transducers separated in the streamwise direction and a wall-shear stress wire placed immediately behind the downstream pressure transducer. The configurations used are shown in figure 7. Additional configurations involved rotation of the rake through 90° for spanwise correlations above the boundary layer, and use of the two wall pressure sensors, one fixed and the other moved either upstream or in the spanwise direction from it.

Conventional Wall-Pressure Correlations

(R_{pp} $(\underset{\sim}{r},\tau)$ is coefficient of correlation between pressure fluctuations at $(\underset{\sim}{x},t)$ and $(x + \underset{\sim}{r},\ t + \tau)$: R_{pu}, etc, denote pressure-velocity correlations).

$R_{pp}(r,\ \tau)$: The purpose of these data is to improve on the data of Willmarth and Wooldridge (1962) for which the non-dimensional transducer diameter was 500. They also used high-pass filtering ($f > 110$ Hz) to remove low-frequency spurious contributions to the wall pressure spectrum. Blake (1970) used a pinhole transducer to remove resolution problems, although the resonance frequency was at 17.5 kHz, somewhat low for turbulence spectra. Wills (1967) also had problems of low frequency contributions to the spectra. These data are therefore worth re-publishing; in particular measurements of ϕ_{pp} $(k_1, U_{ph}/U_e)$ are of crucial importance to log-law arguments. Here $U_{ph} = \omega/k_1$, phase velocity.

The effectiveness of the back-off can be assessed since from Phillips' (1955) theorem:

$\iint R_{pp}\, dx\, dz = 0$ and in particular, if the main source term of the Poisson equation is $\frac{\partial U}{\partial y} \frac{\partial v}{\partial x}$ then $\int R_{pp}\, dx = 0$.

R_{pu} R_{pv} R_{puv} $(\underset{\sim}{x},\ \tau)$: These again improve on and extend the old measurements of Willmarth and Wooldridge (1963) - free stream correlations also assess the effectiveness of the back-off. Sharp gradients around zero time-delay for the correlation of shear stress with wall pressure give an a priori justification for using the shear stress for log-region event detection.

Rpe_{xy} $Rp\omega_z$ $Rp\,\frac{\partial v}{\partial y}$ $(\underset{\sim}{x},\tau)$: These data are new and provide wave-number-limited estimates of the spanwise vorticity and strain-rate contributions to the wall pressure. From the cross-spectra of these quantities, contributions of difference wave-number ranges of the strain rate and vorticity to the wall

pressure fluctuations can be estimated. $R_p \frac{\partial v}{\partial x}$ is important in assessing the relative contributionsto the source term of Poisson's equation. It also checks Mulhearn's (1975) predictions of R_{pu}, R_{pv} calculated by rapid distortion theory and thus uses only the main source term, $\frac{\partial U}{\partial y} \frac{\partial v}{\partial x}$. It is also important in the predictions of ϕ_{pp} by Panton and Linebarger (1974).

ω_z and e_{xy} will also be used in the VITA detection algorithm for comparison with the uv signature.

$\underline{R_{11}(0,0,r) \quad R_{22}(0,0,r)}$

These free-stream data are a check of Phillips' (1955) theorem and extensions of it by Wood and Ferziger (1984).

Literature cited

1. Ajagu, C.O., Libby, P.A. and La Rue, J.C. Modified gauge for time-resolved skin-friction measurements. Rev.Sci.Instrum.53, 1920, 1982.

2. Alfredsson, P.H. and Johansson, A.V. On the detection of turbulent generating events. J. Fluid Mech.139, 325, 1984.

3. Andreopoulos, J. and Bradshaw, P. The thermal boundary layer far downstream of a spanwise line source of heat. Trans.ASME J. Heat Transfer 102, 755, 1980.

4. Bellhouse, B.J. and Schultz, D.L. The measurement of fluctuating skin friction in air with heated thin-film gauges. J. Fluid Mech. 32, 675, 1968.

5. Bian, Y.Z., Morrison, J.F. and Bradshaw, P. Measurements of the correlation between the fluctuating wall pressure and the fluctuating longitudinal velocity in a turbulent boundary layer. Imperial College Aero TN 82-107, 1982.

6. Blackwelder, R.F. and Kaplan, R.E. On the wall structure of the turbulent boundary layer. J. Fluid Mech. 76, 89, 1976.

7. Blackwelder, R.F. and Haritonidis, J.H. The bursting frequency in turbulent boundary layers. J. Fluid Mech. 132, 87, 1983.

8. Blake, W.K. Turbulent boundary layer wall pressure fluctuations on smooth and rough walls. J. Fluid Mech. 44, 637, 1970.

9. Bradshaw, P. Irrotational fluctuations near a turbulent boundary layer. J. Fluid Mech. 27, 209, 1967a.

10. Bradshaw, P. Inactive motion and pressure fluctuations in turbulent boundary layers. J. Fluid Mech. 30, 241, 1967b.

11. Bradshaw, P. and Koh, Y.M. A note on Poisson's equation for pressure in a turbulent flow. Phys.Fluids 24, 777, 1981.

12. Bull, M.K. and Thomas, A.S.W. High frequency wall pressure fluctuations in turbulent boundary layers. Phys.Fluids 19, 597, 1976.

13. Chambers, F.W., Murphy, M.D. and McEligot, D.M. Laterally converging flow II: temporal wall shear stress. J. Fluid Mech. 127, 403, 1983.

14. Chen, C.P. and Blackwelder, R.F. Large scale motion in a turbulent boundary layer: a study using temperature contamination. J. Fluid Mech. 89, 1, 1978.

15. Corino, E.R. and Brodkey, R.S. A visual observation of the wall region in turbulent flow. J. Fluid Mech. 37, 1, 1969.

16. Gaudet, L. The influence of transducer misalignment on the measurement of fluctuating surface pressure at low speed. R.A.E. Tech.Memo.Aero 1752, 1978.

17. Goldman, A. and Chung, C.H. Impedance of an orifice under a turbulent boundary layer with pressure gradient. J. Acoust.Soc.Am. 71, 573, 1982.

18. Johansson, A.V. and Alfredsson, P.H. On the structure of turbulent channel flow. J. Fluid Mech. 122, 295, 1982.

19. Mulhearn, P.J. On the structure of pressure fluctuations in turbulent shear flow. J. Fluid Mech. 71, 801, 1975.

20. Murlis, J., Tsai, H.M. and Bradshaw, P. The structure of turbulent boundary layers at low Reynolds numbers. J. Fluid Mech. 122, 13, 1982.

21. Offen, G.R. and Kline, S.J. Combined dye-streak and hydrogen-bubble visual observations of a turbulent boundary layer. J. Fluid Mech. 62, 223, 1974.

22. Panton, R.L. and Linebarger, J.H. Wall pressure spectra calculations for equilibrium boundary layers. J. Fluid Mech. 65, 261, 1974.

23. Phillips, O.M. The irrotational motion above a free turbulent boundary. Proc. Camb. Phil. Soc 51, 220, 1955.

24. Robinson, S.K. An experimental search for near-wall boundary conditions for L.E.S. AIAA-82-0963. NASA Ames 1982.

25. Subramanian, C.S., Rajagopalan, S., Antonia, R.A. and Chambers, A.J. Comparison of conditional sampling techniques in a turbulent boundary layer. J. Fluid Mech. 121, 123, 1982.

26. Thomas, A.S.W. Conditionally sampled measurements of the fluctuating pressure at the wall beneath a turbulent boundary layer. AIAA 78-1157.

27. Wills, J.A.B. Spurious pressure fluctuations in wind tunnels. N.P.L. Aero Report 1237, 1967.

28. Willmarth, W.W. and Wooldridge, C.E. Measurements of the fluctuating pressure at the wall beneath a turbulent boundary layer. Univ. Michigan, Dept. Aero. and Astro. Engg. O.R.A. project 02920, 1962.

29. Willmarth, W.W. and Wooldridge, C.E. Measurements of the correlation between the fluctuating velocities and fluctuating wall pressure in a thick turbulent boundary layer. AGARD Rep. 456, 1963.

30. Wood, D.H. and Ferziger, J.H. The potential flow bounded by a mixing layer and a solid surface. Submitted to Proc. Roy. Soc. 1984.

APPENDIX

Review and extension of the VITA sampling algorithm

Introduction

This review documents the reasons for choosing the VITA (Variable Interval Time Averaging) sampling algorithm first used by Blackwelder and Kaplan (1976), in preference to a more straightforward threshold/derivative scheme as used by Murlis et al. (1982). It also highlights certain inadequacies in the VITA algorithm and some modifications are introduced to improve it.

Briefly, the technique calculates the variance of the detection signal over a short-time averaging period, usually set as a simple proportion of inner or outer timescales, δ/U_e or ν/u_τ^2, and a simple threshold criterion is applied to this variance to determine whether the signal is "interesting" or not. From the identity trace thus obtained ($c(t) = 1$ means "interesting"), conditional and ensemble averages of these events can be obtained, namely:

$$\frac{\overline{c(t)\ f(t)}}{\overline{c(t)}} \quad \text{and} \quad \frac{1}{N}\sum_{1}^{N} f(\tau_n + t)$$

where $f(t)$ is the conditioned signal, and τ_n the point of detection.

The results of the technique depend heavily on the threshold and sampling interval used - as does any conditional sampling technique depend on its conditioning criteria. One of the reasons why the VITA technique has been widely used is that Blackwelder and Kaplan showed it to be an unbiased discriminator and genuinely educed features of the detection signal that were not an artifact of the

sampling technique. Johansson and Alfredsson (1982), Robinson (1982), Chambers et al. (1983) and Blackwelder and Haritonidis (1983) have used the technique for the detection of periods of large turbulent fluctuations in the inner layer. Chen and Blackwelder (1978) and Subramanian et al. (1982) have also used it with temperature or temperature-velocity products as the detection signal in outer layer studies.

The choice of detection signal is an important one. Here, we choose to use the instantaneous uv product (from a cross-wire in the log-region of a zero pressure gradient 2D boundary layer). Near-wall bursts, as observed by Corino and Brodkey (1969), are known to contribute to between half and three-quarters of the production of shear stress. We restrict the definition of "bursts" to those near-wall events visually identified in flow visualization studies, whose relationship with log-region disturbances has been also visually established by Offen and Kline (1974). We ascribe to the meaning of "events" no more than periods of large variance in the uv signature; the choice of uv as detection signal is simply the pragmatic requirement of wishing to detect motions principally involved in the production of shear stress.

Alfredsson and Johansson (1984) show that with the use of the u and v signatures, different individual events are detected whilst the uv signature shows significant excursions from the mean. This is confirmed by the present results. The uv signature is of course, more sensitive to the randomness in phase associated with the convection velocity of the event detected. The use of the variance of a signal to detect events does not discriminate between positive and negative contributions to the mean. Thus for the present purposes, a quadrant analysis is applied to the events detected and only those, for which either of the

conditions $u < 0$, $v > 0$ or $u > 0$, $v < 0$ is satisfied, are retained as events. Also the two different contributions, ejection and sweep-type events, are averaged separately. The rationale for doing this is shown by the ensemble-averaged time histories of the wall pressure during these events, which are significantly different.

For the present study of log-region events, we used conventional wires, which have sufficient resolution since the same arguments that demonstrate why a log-law should exist also show that events scale on y (the distance from the wall), assuming that the log-law is an adequate first approximation for these events. Several workers have shown that the VITA technique preferentially detects events of the same duration as the short-time averaging period. This is to be expected since the short-time averaging period (T) behaves as a low-pass filter with 1/T as the cut-off frequency, but can lead to questionable conclusions when features in ensemble-averaged time histories or space-time correlations of duration less than T are interpreted. This is particularly important when burst/event rates or durations are scaled with inner or outer flow variables in order to investigate Reynolds number dependence. The choice between inner, outer or mixed scaling is important. Inner scaling (ν, u_τ) implies that near-wall events or bursts are a consequence of wall flow instability, whilst outer scaling (δ, U_e) implies that they are imposed by large scale disturbances. Neither scaling alone is likely to give Reynolds number independence for both rate and duration of either bursts or log-region events, simply because bursts are intimately related to larger scale disturbances in the log-region and possibly above.

Offen and Kline (1974) cogently argue the difference between spatial and temporal coherence; structures are seen by their spatial coherence even when subjected to

large-scale fluctuations (as is the convection of near-wall events modulated by inactive motions), whereas a temporal record at one or even two points does not necessarily characterise the structure. Therefore sensor data must be interpreted in terms of wavelength rather than period in order to achieve a correlation of data obtained in an Eulerian reference frame with visually observed, spatially coherent structures. The wavelength of the structure is independent of the frame of reference assuming that its convection velocity is the same as the local mean flow. These arguments have important ramifications in the scaling of detection rate or period.

For data obtained in an Eulerian reference frame, VITA detects periods of large temporal gradient; a first order simplification shows that the variance is proportional to the square of the gradient of the linearly approximated signal. Therefore, in order to improve correspondence with visually observed, spatially coherent events, the convection velocity must be equal to the local, short-time averaged velocity. In fact VITA tends to minimise this discrepancy by its bias for detecting events of lengths of about the same size as T, for which the difference between the short-time average velocity and the convection velocity is the least.

Description of Algorithm

The short-time variance of a fluctuating quantity x is

$$\hat{x} = \frac{1}{T}\int_{t-T/2}^{t+T/2} (x - \breve{x})^2 \, dt$$

where

$$\breve{x} = \frac{1}{T}\int_{t-T/2}^{t+T/2} x \, dt$$

For discrete data

$$\hat{\breve{x}} = \frac{1}{n-1}\sum_{1}^{N} (x_i - \tilde{x})^2$$

$$\equiv \frac{1}{n-1}\sum_{1}^{N} x_i^{\,2} - \tilde{x}^2$$

$$\equiv \widetilde{x^2} - \tilde{x}^2$$

T is the short-time averaging period and short-time averages tend to conventional averages as $T \to \infty$.

The sampling criterion is:

$$ID(t) = 1 \quad \text{for } x > \kappa\, \overline{x^2}$$

$$= 0 \quad \text{otherwise.}$$

In the case of uv as the detection signature, the threshold criterion becomes:

$$ID(t) = 1 \quad \text{for } \widehat{uv} > \kappa\, \overline{u^2}\,\overline{v^2}.$$

The threshold of $k\, \overline{u^2}\, \overline{v^2}$ is regarded as being more physically meaningful than $\overline{(uv)}^2$.

The secondary criterion, where events are sorted according to the sign of the u signature at the centre of the event is:

$$ID^+(t) = 1 \quad \text{for } u > 0 \quad v < 0$$

$$ID^-(t) = 1 \quad \text{for } u < 0 \quad v > 0$$

All detections for $u > 0$, $v > 0$ or $u < 0$, $v < 0$ are rejected. Thus contributions to uv in the second and fourth quadrants are regarded as the most significant events and major contributors to the production of uv. $ID(t)$ is simply the sum of $ID^{+}(t)$ and $ID^{-}(t)$. Identity ratios can be defined so that:

$$\nu^{+}\,\overline{\tilde{x}}^{+} + \nu^{-}\,\overline{\tilde{x}}^{-} + (1-\nu)\,\overset{\smile}{\overline{x}} = \overline{x}$$

where the notation of Kovasznay et al. (1970) is extended so that 'turbulent' averages comprise positive and negative events denoted by the superscripts + and $-$. $ID(t) = \nu$.

In order to avoid multiple detection of single events, the detection sequence is switched off for the duration of the event. Short-time averaging periods abut, and on detection sampling is applied to successive data points both before and after the centre of the short-time averaging period that first gave the detection. The length of the event is the difference between the first and last data points that satisfy the sampling criterion.

For future data, the bias of event lengths towards one of about the same length as the short-time averaging period is removed by using a simple threshold discriminator to estimate the event length - once it has been detected by the value of the variance criterion. An unbiased estimate of event lengths is crucial to their correct scaling.

Ensemble-averaged time histories of N samples are defined by:

$$< f(t) > = \frac{1}{N} \sum_{1}^{N} f(\tau_n + t)$$

where τ_n is taken as the centre of the event, and t the time displacement both before and after τ_n over which the sample is taken.

The reason for using a 'level' criterion rather than one of 'slope' for the secondary criterion is purely pragmatic. Inspection of instantaneous velocity or uv traces shows the ambiguity with which a gradient decision can be made within a short-time average period, even for an average gradient over the period of T. Perhaps the more pertinent point is that $u > 0$ or $u < 0$ is the relevant criterion where events are either a structure with low streamwise momentum being lifted away from the wall, or conversely being pushed toward the wall with an excess of momentum compared to the rest of the fluid around it. The terms acceleration or decceleration used by Corino and Brodkey (1969) are probably a result of visual observation of these events where one can follow the path of the structure: say, an acceleration or sweep ($u > 0$, $v < 0$) which is pushed in toward the wall into a region of <u>less</u> streamwise momentum. A fixed probe merely sees the original event with streamwise momentum greater than that of its surroundings.

An estimate for the highest frequency component measured by a fixed probe is given by the Kolmogorov length scale divided by a convection velocity, not the Kolmogorov timescale which is a measure of the duration of an eddy before its energy is dissipated. Using inviscid scales for an estimate of ε, the turbulent energy dissipation rate,

$$\frac{\eta}{U_c} = \left(\frac{u_\tau \delta}{\nu}\right)^{-3/4} \frac{\delta}{U_c}$$

$$\tau = \left(\frac{u_\tau \delta}{\nu}\right)^{-1/2} \frac{\delta}{u_\tau}$$

$$\tau : \frac{\eta}{U_c} = \frac{R^{1/4}}{u_\tau} : \frac{1}{U_c}$$

Assuming $U_c \sim 10u_\tau$ say, then

$$\tau : \eta/U_c \equiv 10R^{1/4}$$

$R^{1/4}$ is a weak function and so the ratio of the Kolmogorov timescale to convected Kolmogorov length-scale is of order ten. Thus the above argument is crucial to the correct setting of the sampling interval if one is to be able to sample events of the order of the Kolmogorov scales. In practice the sampling interval required by the above arguments is limited by the recording equipment. Also the sizes of events detected is set to a minimum by the sensor size. Therefore the values used here are that the sampling interval is twice the frequency response of the analog recording equipment (40 kHz) which is about the same frequency of a convected length-scale of the Kolmogorov

length-scale and T is set to equal the time duration of a 1 mm length-scale, the sensor size. These arguments hold for moderate to large Reynolds numbers.

Captions

Fig.1(a) Ensemble time averaged histories (sweeps).
Threshold = 0.3. $y/\delta = 0.114$.

Fig.1(b) Ensemble time averaged histories (sweeps).
Threshold = 0.4. $y/\delta = 0.470$.

Fig.2(a) Ensemble time averaged histories (ejections).
Threshold = 0.3. $y/\delta = 0.114$.

Fig.2(b) Ensemble time averaged histories (ejections).
Threshold = 0.4. $y/\delta = 0.470$.

Fig.3(a) Pdf distributions: uv detection

u - u-compt. of velocity
v - v-compt. of velocity
p - wall pressure
S - shear stress uv
T - wall shear stress

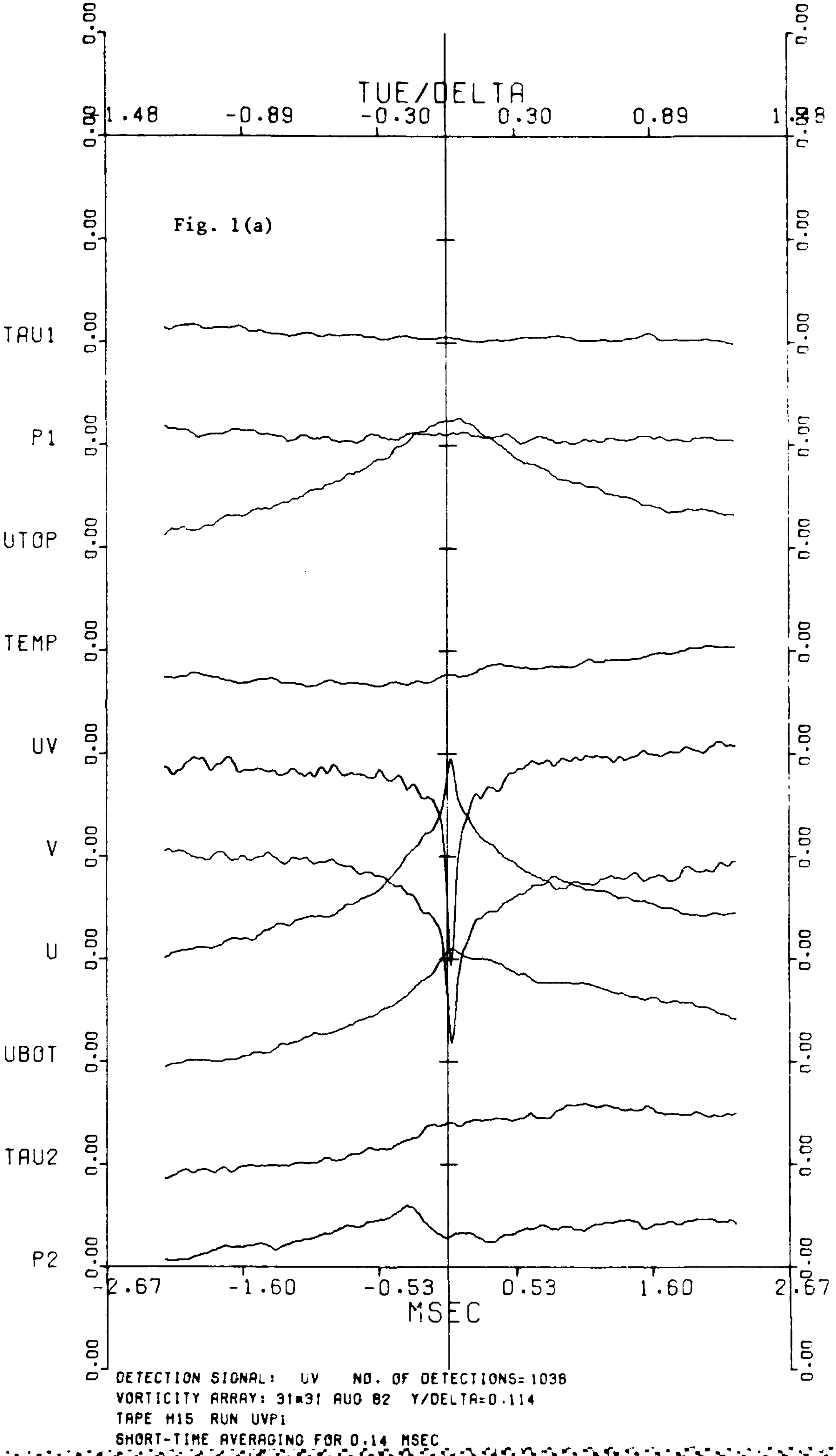
The lower curves are conventional pdf's, the upper conditional.

$T/\Delta T$ - event lengths

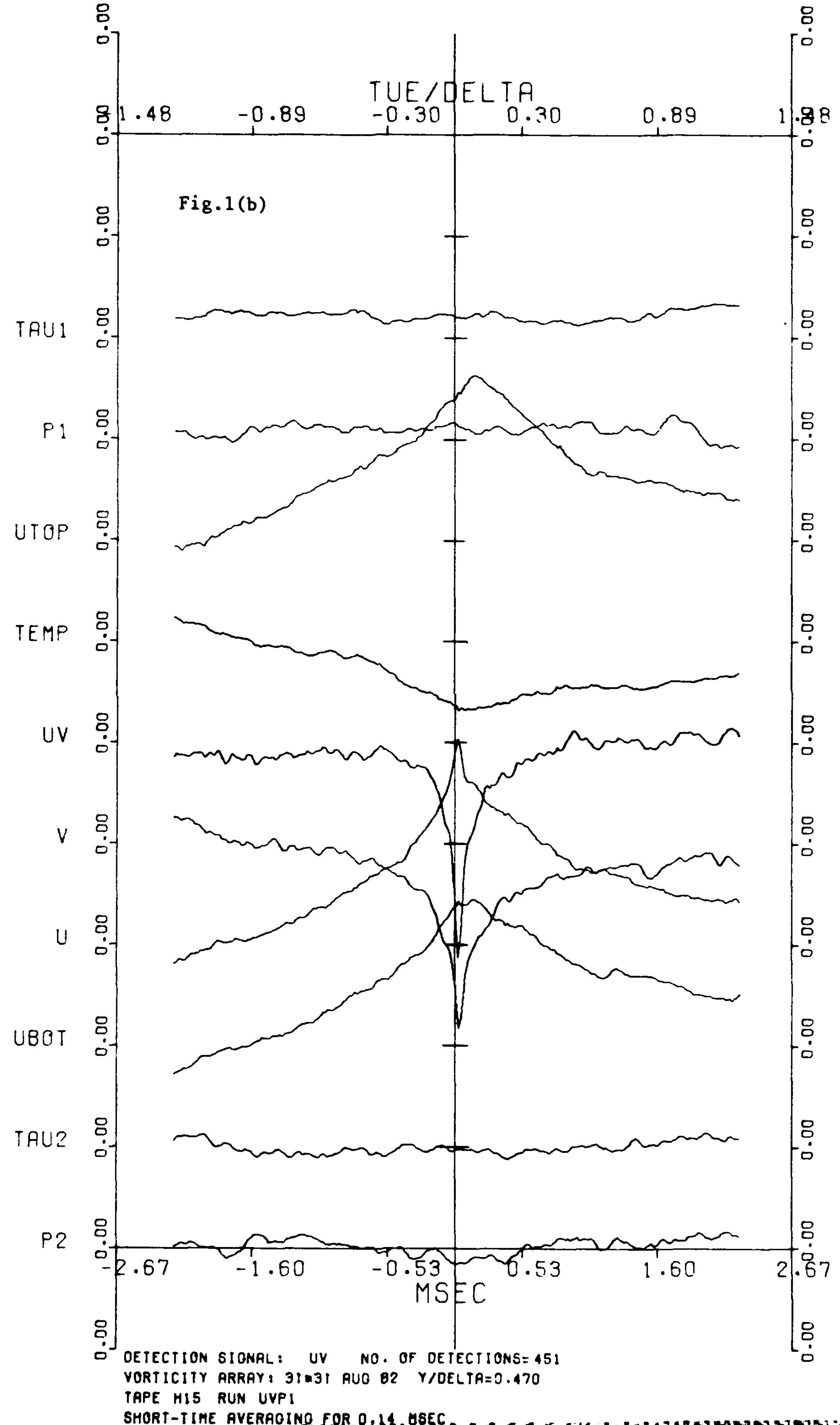
Fig.3(b) Pdf distributions : u detection

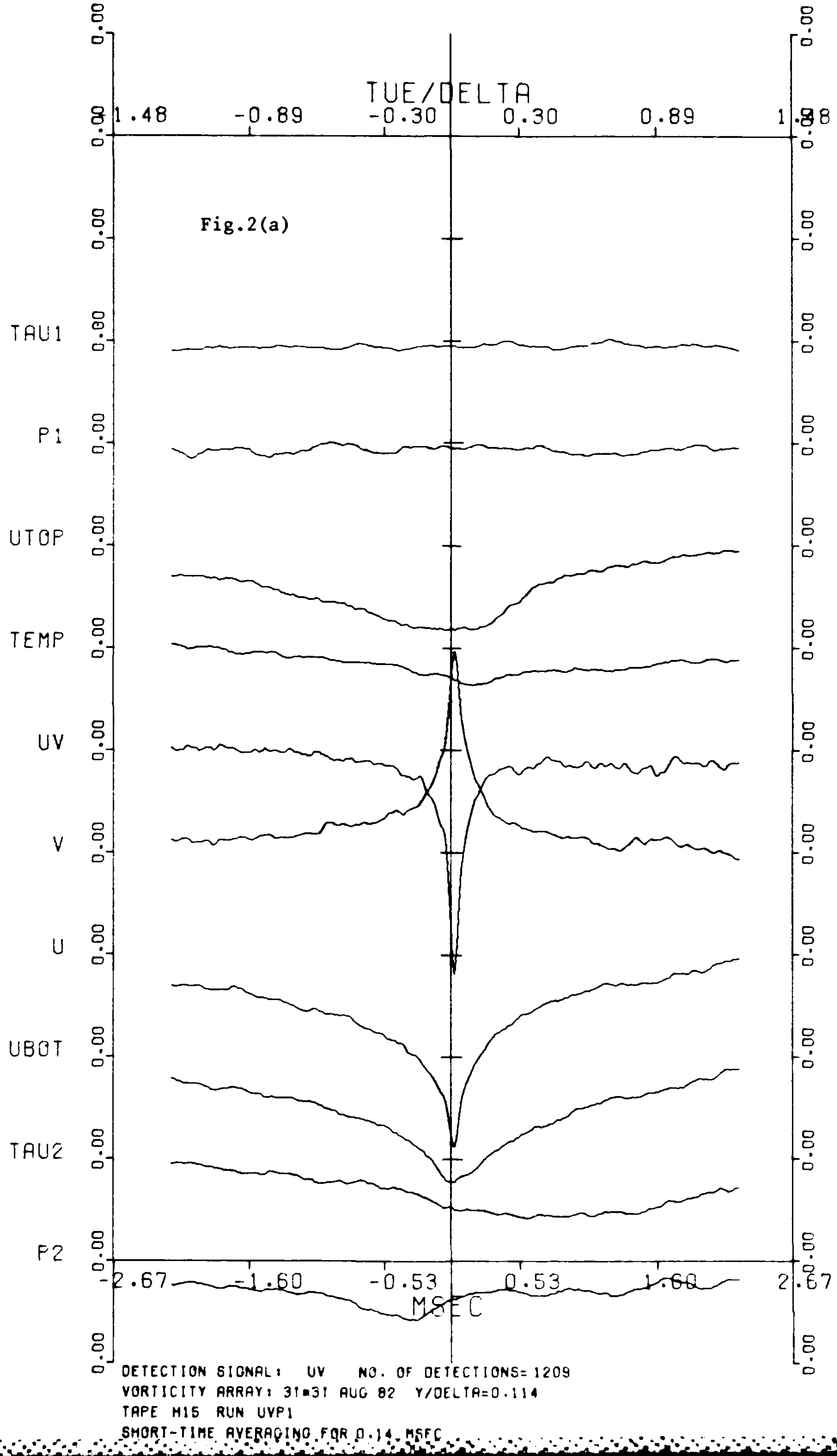
Fig.3(c) Pdf distributions : v detection

Fig.4	$R_{\overline{pu}}$ correlations : no high pass filtering.
Fig.5(a)	Analogue wall pressure spectrum $\int\phi(\omega)\ dw = \overline{p^2}$
Fig.5(b)	Digital wall pressure spectra.
Fig.6(a)	Space-time correlation $R_{\overline{pp}}$; $x/\delta = .25$, $z/\delta = 0.0$
Fig.6(b)	Space-time correlation $R_{\overline{pu}}$ $R_{\overline{pv}}$ $R_{\overline{puv}}$ $y/\delta = .054$, $z/\delta = 0.0$
Fig.6(c)	Spectra of wall pressure, $\frac{\partial v}{\partial x}$, vorticity (w_z), strain rate (e_{xy})
Fig.6(c) cont.	Space-time correlations $\overline{p\frac{\partial v}{\partial x}}$, $\overline{pe_{xy}}$ and $\overline{pw_z}$
Fig.7	Summary of configurations
Fig.8(a)	Low-law plot
Fig.8(b)	Comparison of VITA detection using u, v and uv signatures
Fig.8(c)	Event length and frequency variation with short-time averaging period.

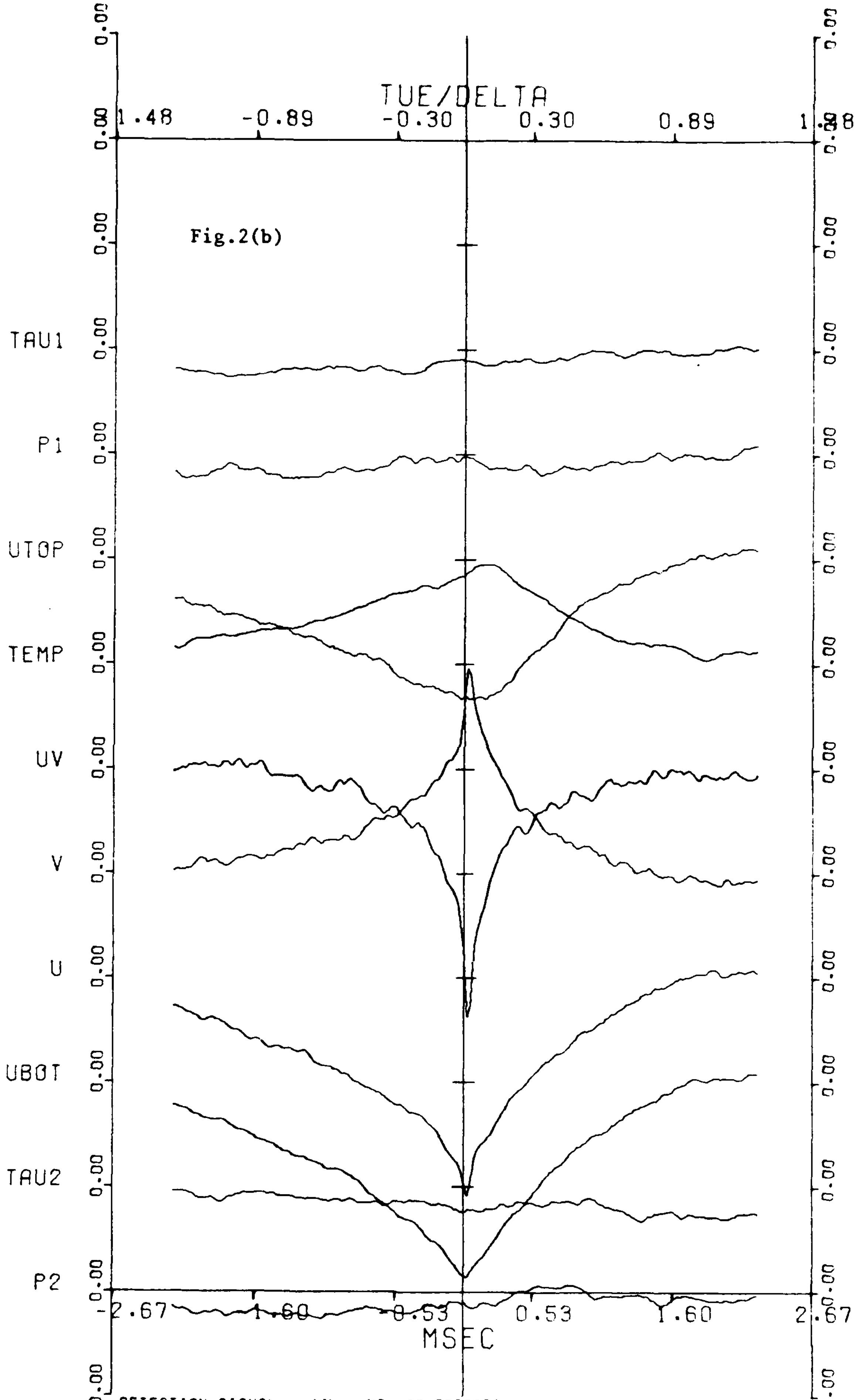


TUE/DELTA
-1.48
-0.89
-0.30
0.30
0.89
1.48
Fig. 1(a)
TAU1
P1
UTOP
TEMP
UV
V
U
UBOT
TAU2
P2
0.00
-2.67
-1.60
-0.53
0.53
1.60
2.67
MSEC
DETECTION SIGNAL: UV NO. OF DETECTIONS= 1038
VORTICITY ARRAY: 31x31 AUG 82 Y/DELTA=0.114
TAPE H15 RUN UVP1
SHORT-TIME AVERAGING FOR 0.14 MSEC


TUE/DELTA
-1.48
-0.89
-0.30
0.30
0.89
1.48
Fig.1(b)
TAU1
P1
UTOP
TEMP
UV
V
U
UBOT
TAU2
P2
-2.67
-1.60
-0.53
0.53
1.60
2.67
MSEC
DETECTION SIGNAL: UV NO. OF DETECTIONS= 451
VORTICITY ARRAY: 31*31 AUG 82 Y/DELTA=0.470
TAPE H15 RUN UVP1
SHORT-TIME AVERAGING FOR 0.14 MSEC



TUE/DELTA
1.48
-0.89
-0.30
0.30
0.89
1.48
Fig.2(a)
TAU1
P1
UTOP
TEMP
UV
V
U
UBOT
TAU2
P2
-2.67
-1.60
-0.53
0.53
1.60
2.67
MSEC
DETECTION SIGNAL: UV NO. OF DETECTIONS= 1209
VORTICITY ARRAY: 31*31 AUG 82 Y/DELTA=0.114
TAPE M15 RUN UVP1
SHORT-TIME AVERAGING FOR 0.14 MSEC



DETECTION SIGNAL: UV NO. OF DETECTIONS= 667
VORTICITY ARRAY: 31*31 AUG 82 Y/DELTA=0.470
TAPE H15 RUN UVP1
SHORT-TIME AVERAGING FOR 0.14 MSEC

Fig. 3a

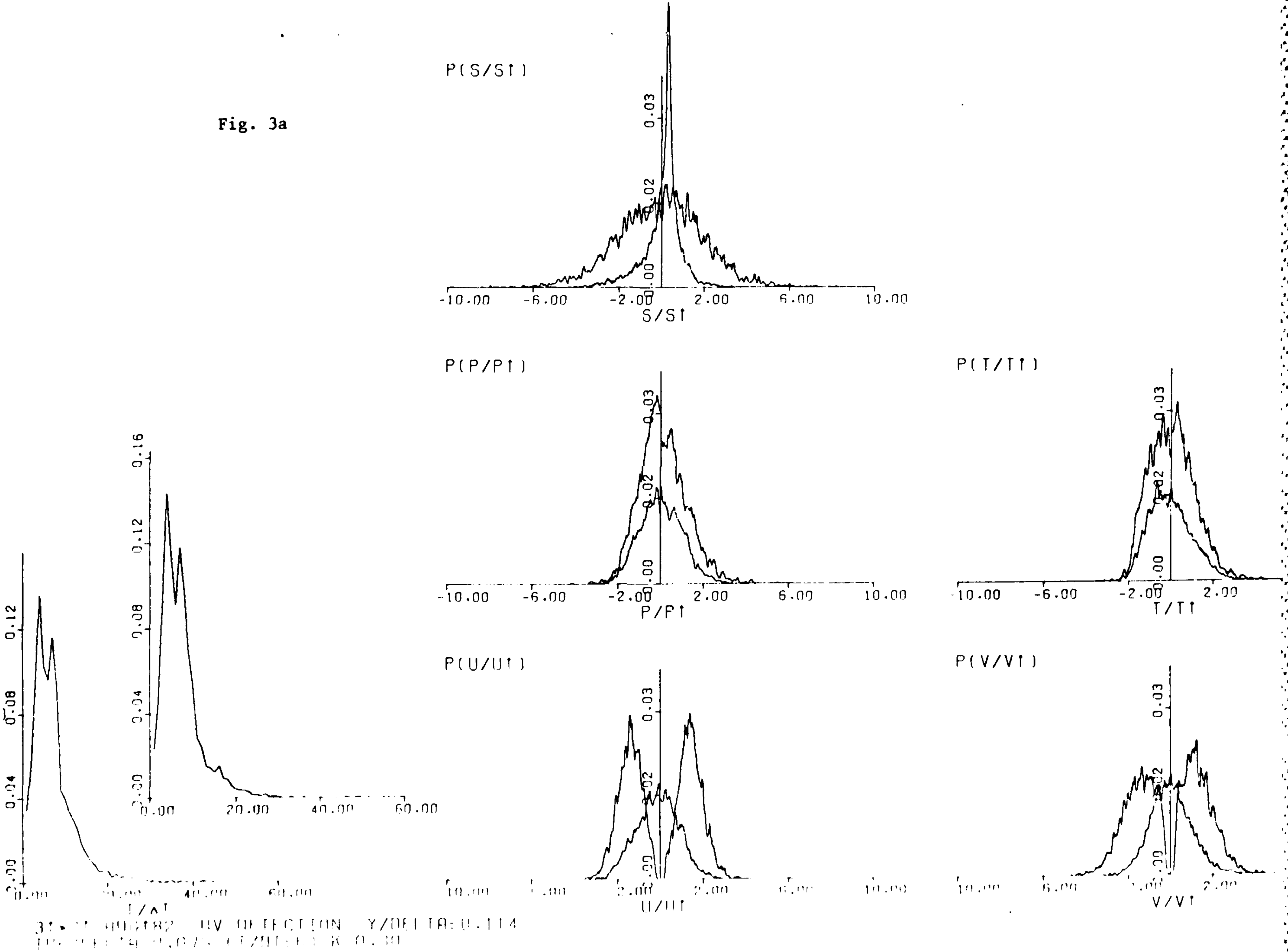
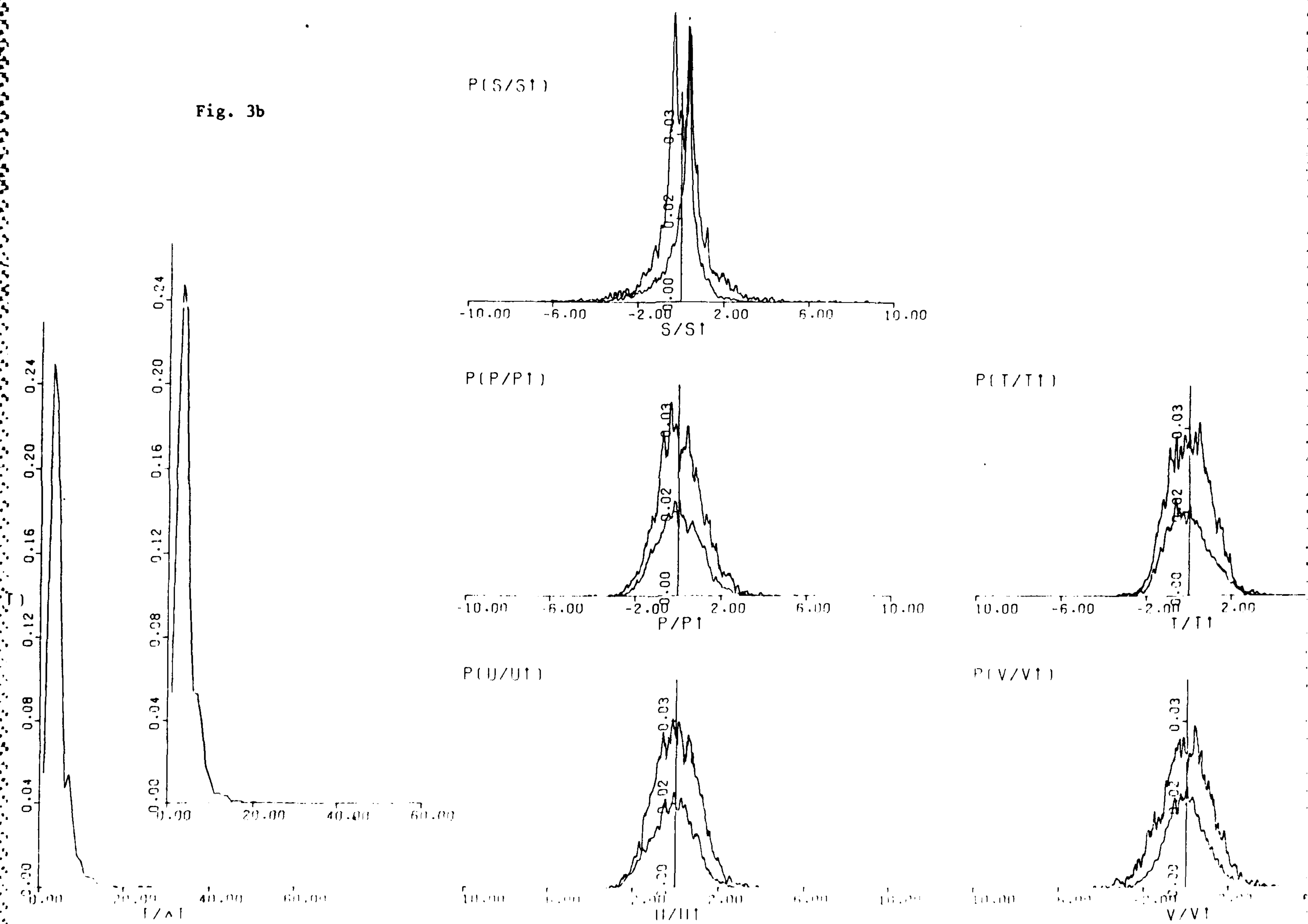


Fig. 3b



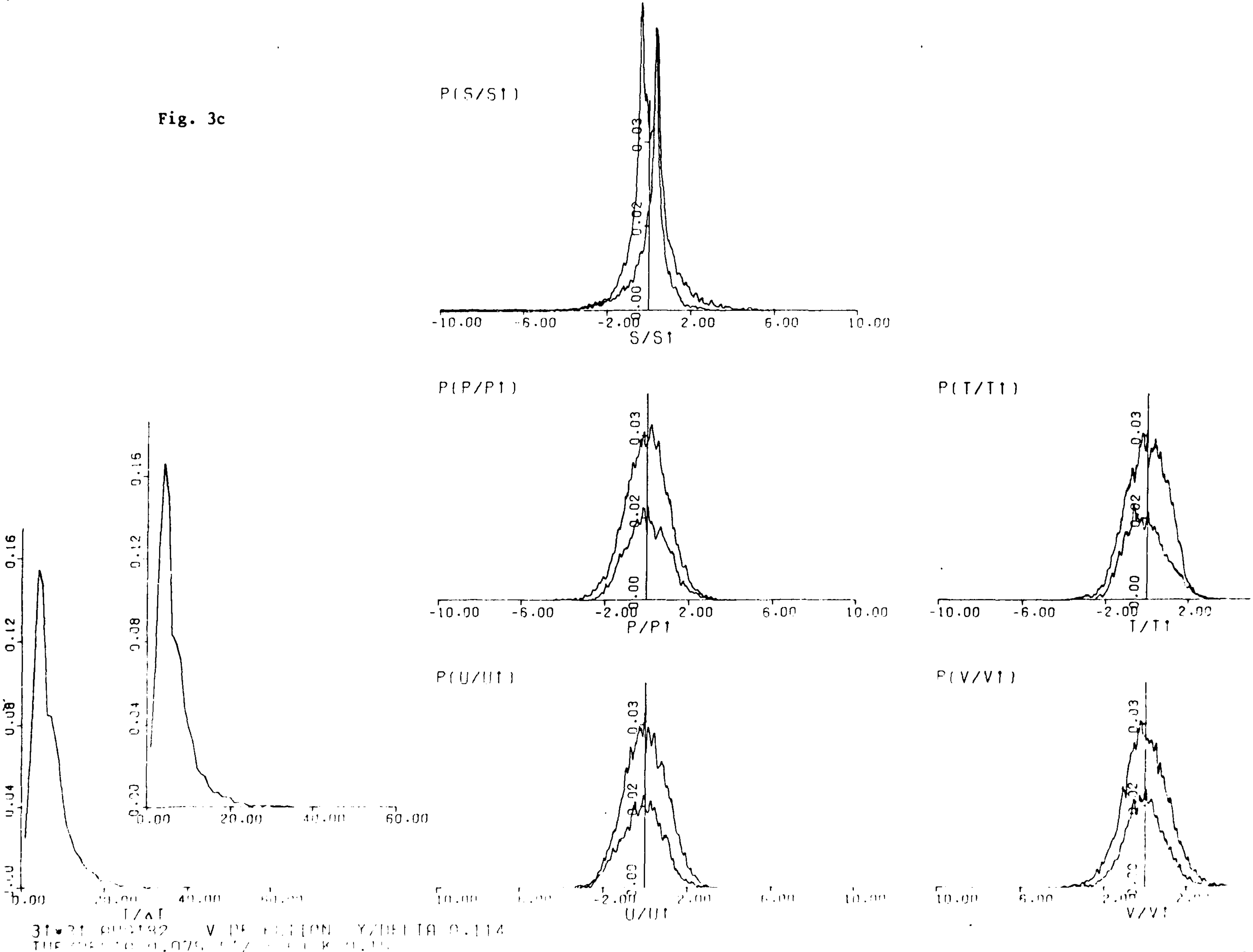
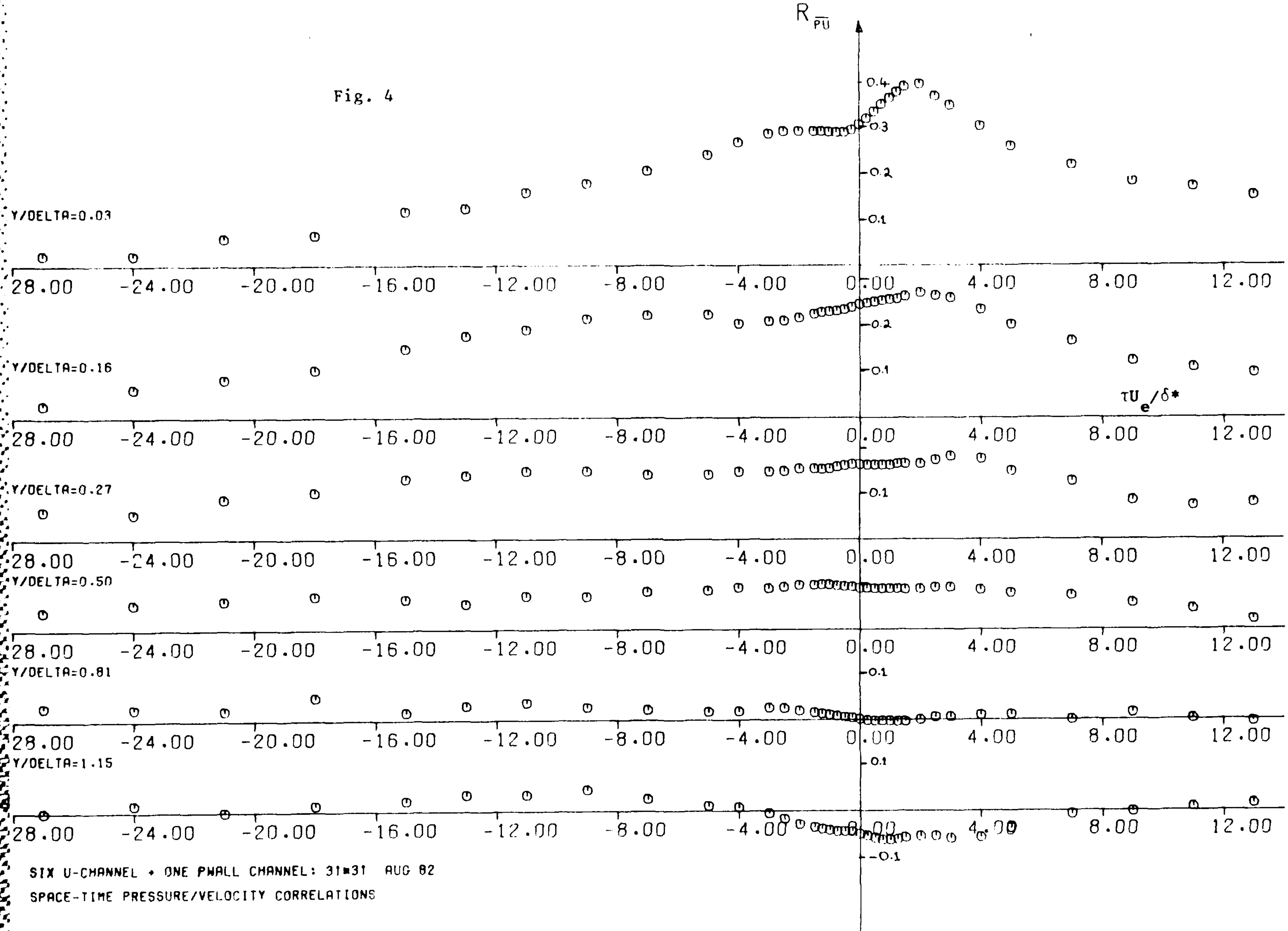


Fig. 3c

Fig. 4



SIX U-CHANNEL + ONE PWALL CHANNEL: 31*31 AUG 82

SPACE-TIME PRESSURE/VELOCITY CORRELATIONS

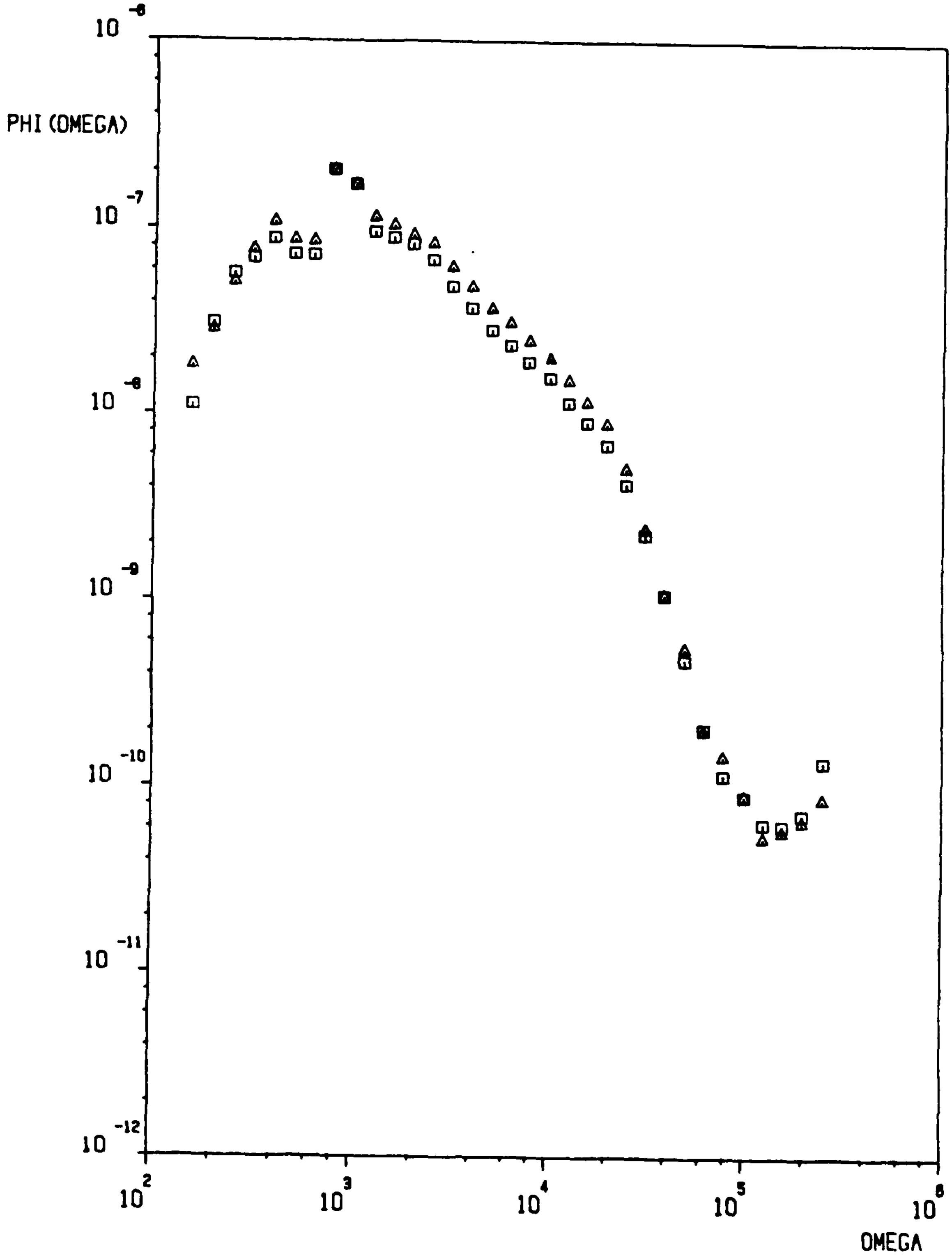
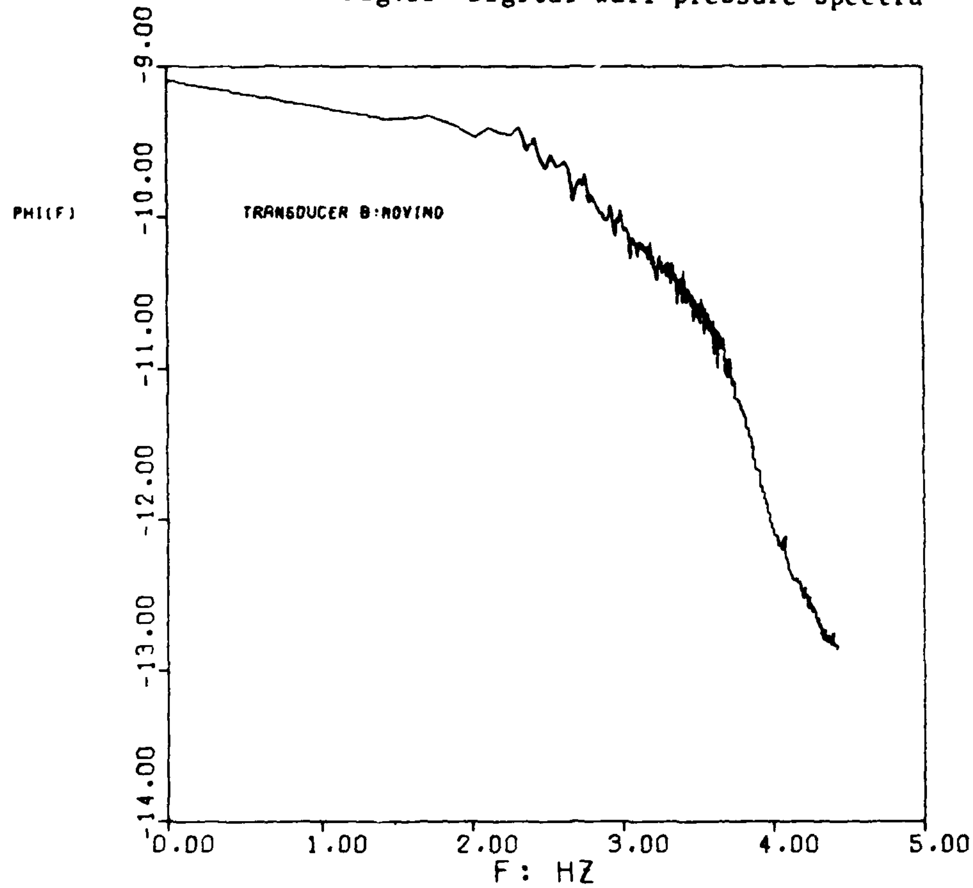


Fig.5a WALL PRESSURE SPECTRA

Fig.5b Digital wall pressure spectra



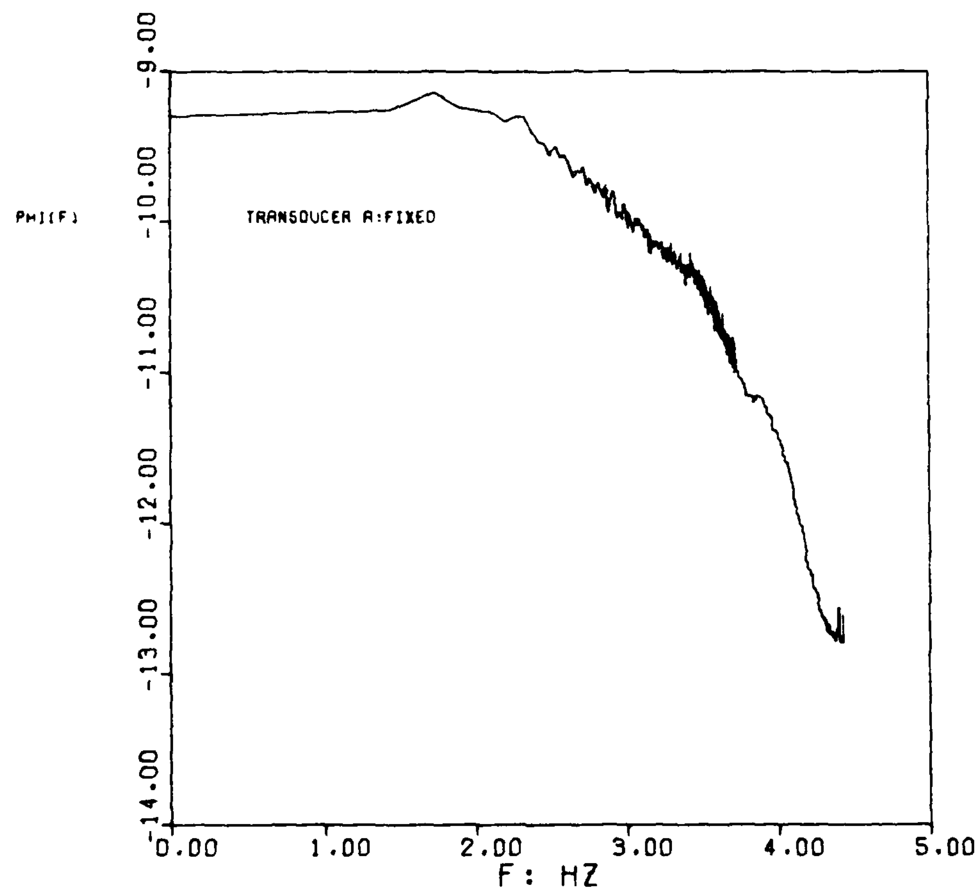
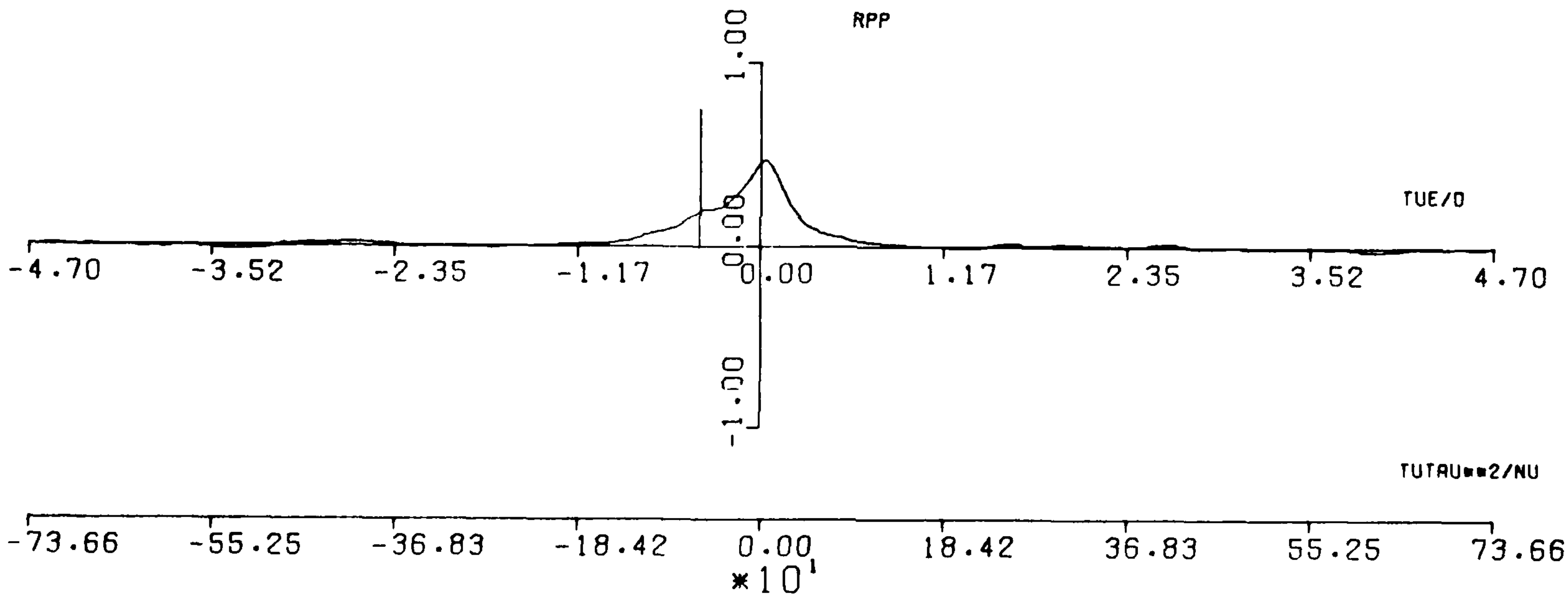


Fig.6a

WALL PRESSURE DATA: 31*31 AUG183



WALL PRESSURE DATA (X-WIRE): 31=31 MAY184

Fig.6(b) Space-time correlation $R_{\overline{pu}}$ $R_{\overline{pv}}$ $R_{\overline{puv}}$

y/δ = .054, z/δ = 0.0

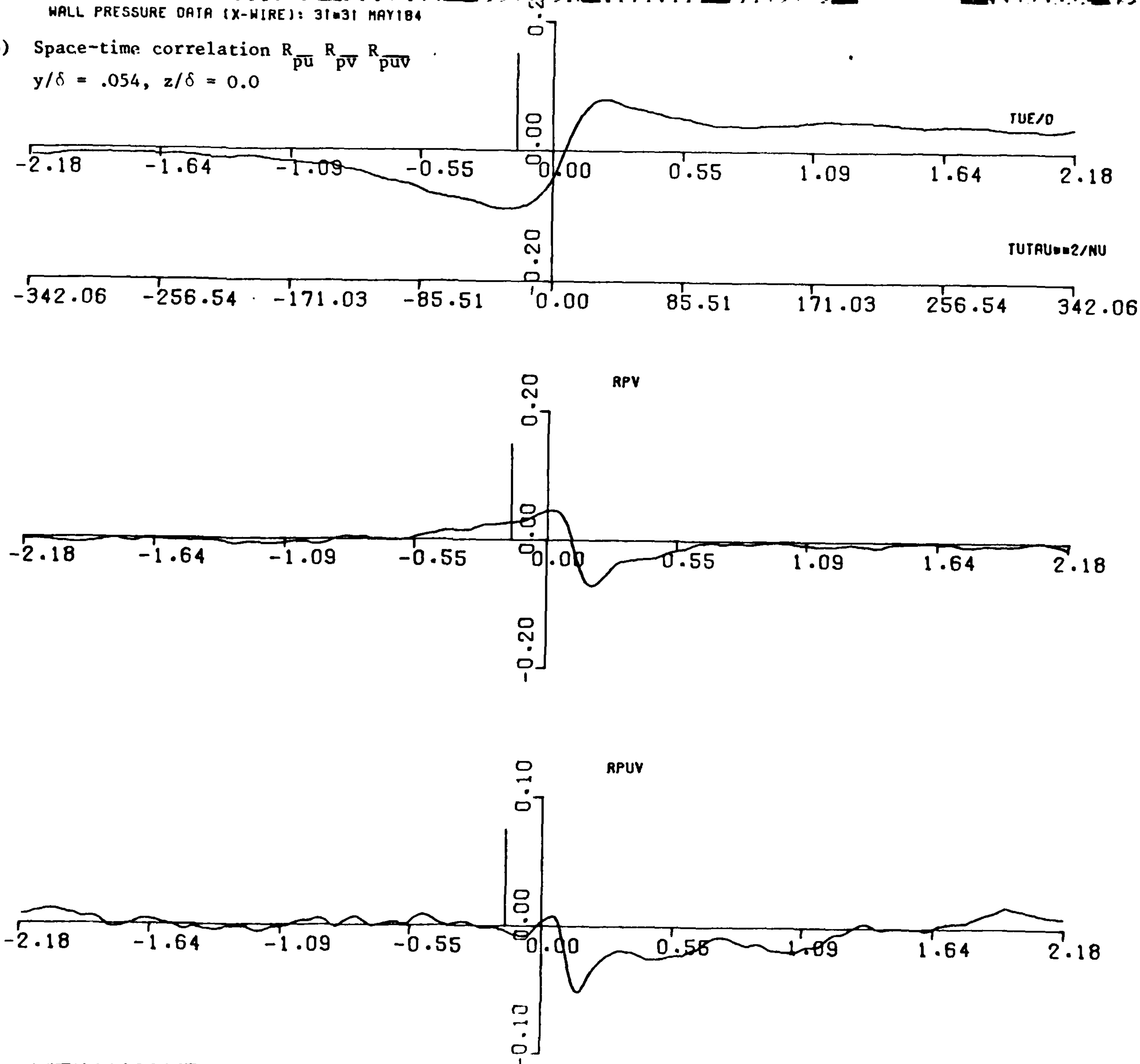
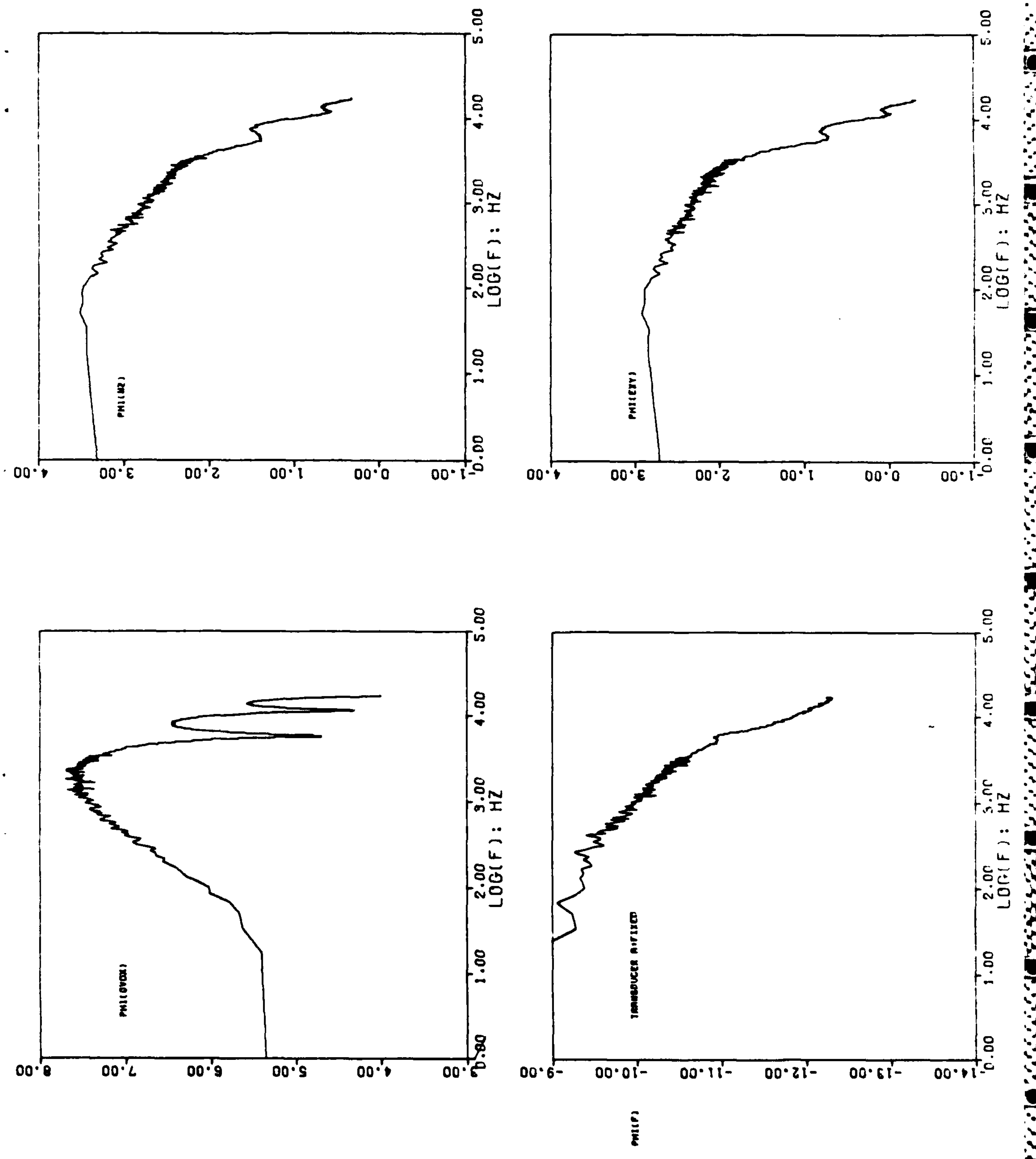
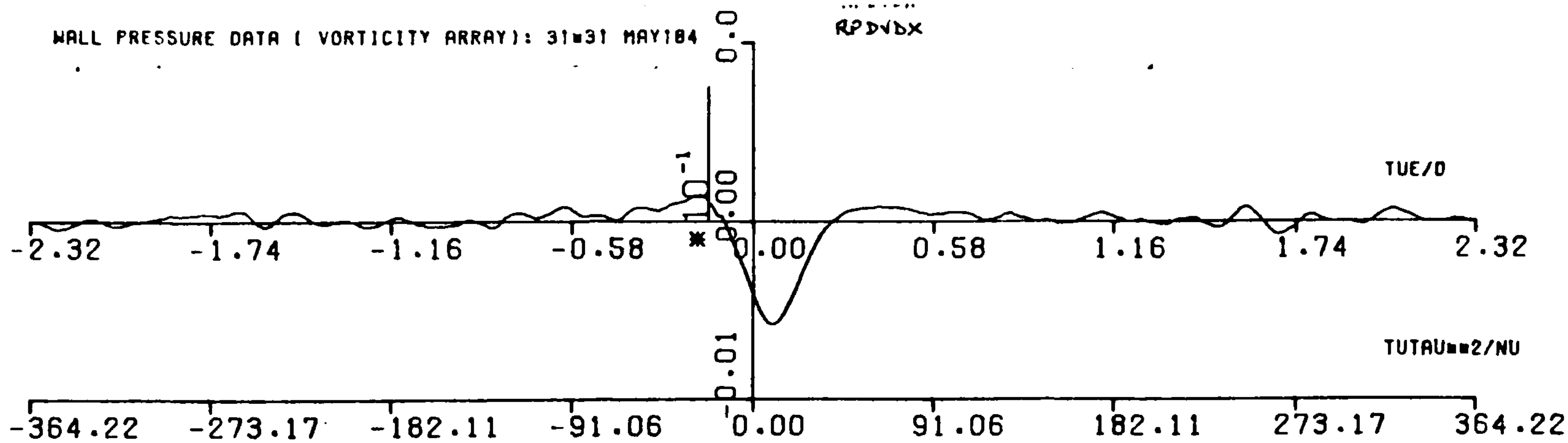


Fig.6(c) Spectra of wall pressure, $\frac{\partial v}{\partial x}$, vorticity and strain rate.





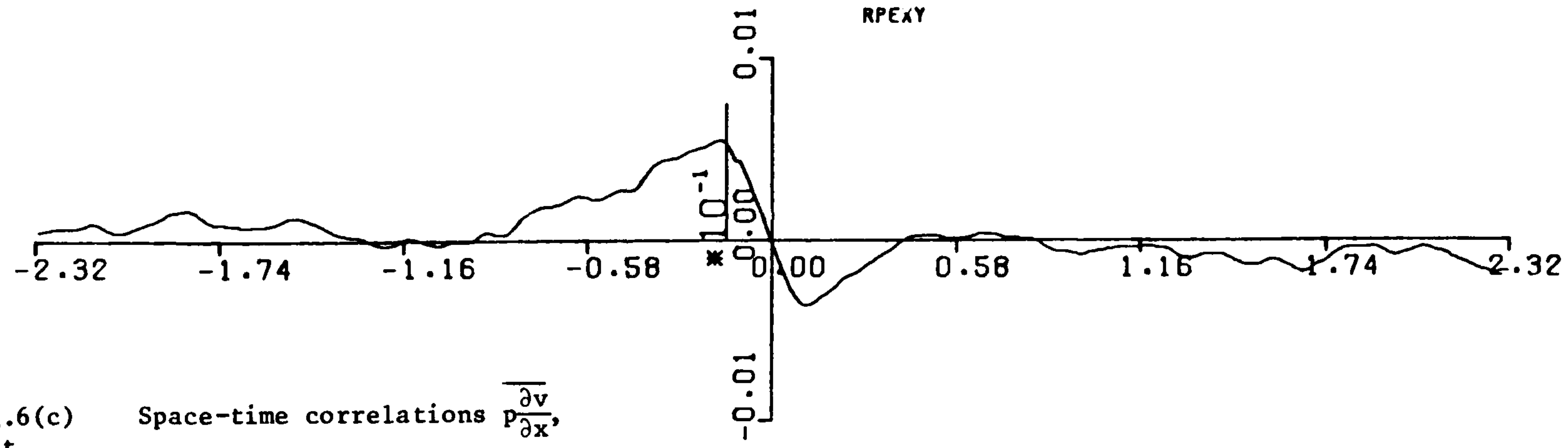
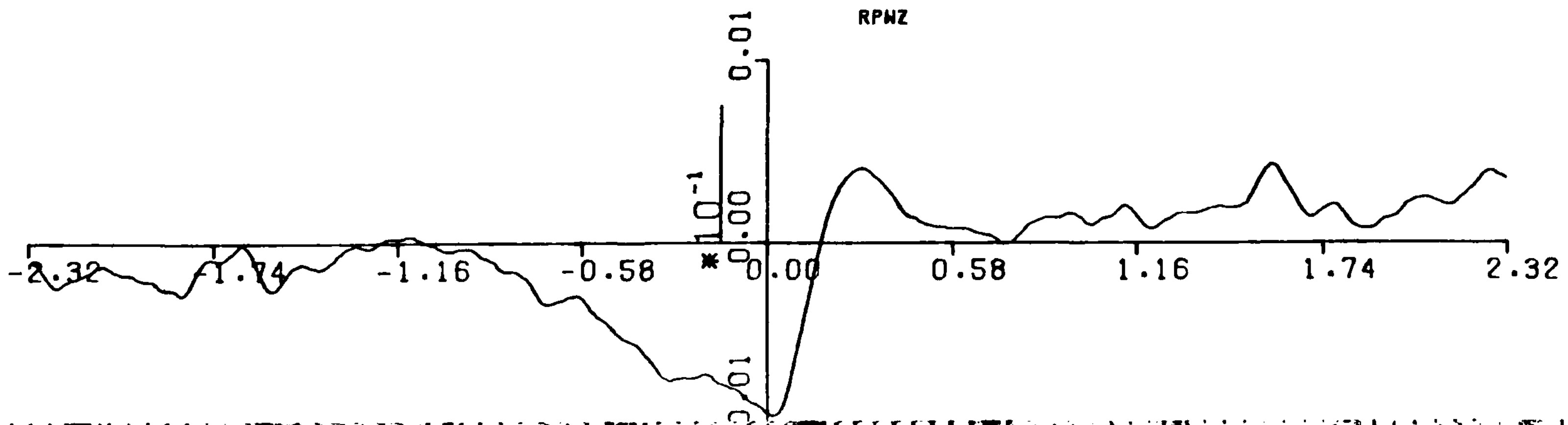
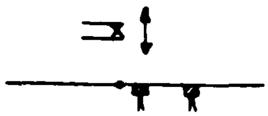


Fig.6(c) cont. Space-time correlations $\overline{p\frac{\partial v}{\partial x}}$, $\overline{pe}_{xy}$ and $\overline{pw}_z$



(i)

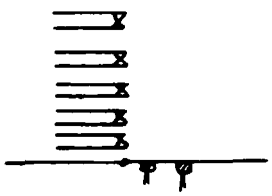


(1) Conventional wall-pressure/wall-shear velocity correlations.

R_{pu} R_{pv} R_{puv} $R_{\tau u}$ $R_{\tau v}$ $R_{\tau uv}$

(2) VITA defined event statistics using wall pressure as a diagnostic.

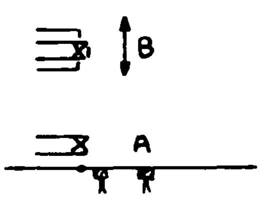
(ii)



(1) Conditional correlations R_{pu} R_{pv} for positive and negative events, and ensemble-averaged time histories

(2) Instantaneous/Ensemble-averaged velocity profiles.

(iii)



(1) Conventionalcorrelations of strain rate (e_{xy}) and vorticity (ω_z) with wall pressure (space-time) and spectra.

(2) Comparison of $< R_{pu} >^{+/-}$ $< R_{pv} >^{+/-}$ using uv, e_{xy}, ω_z as detection signatures

(3) $< R_{p\omega z} >$ $< R_{pexy} >$

(4) 2-point conditional correlations: 'A' using VITA defined events, 'B' using temperature defined intermittency criteria.

Fig.7 Data Summary - configurations.

Fig.8a   Log-law plot.

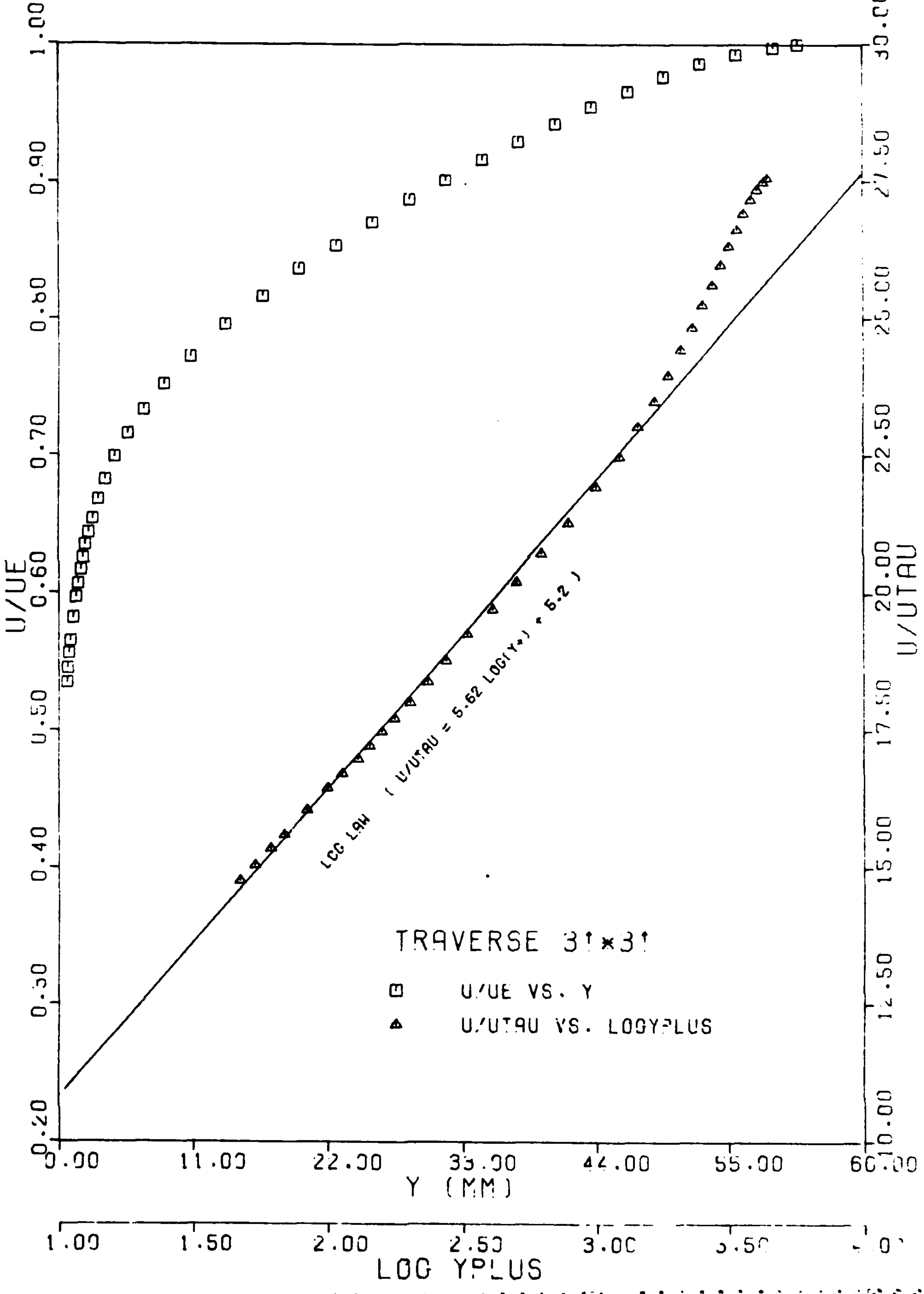


Fig.8b

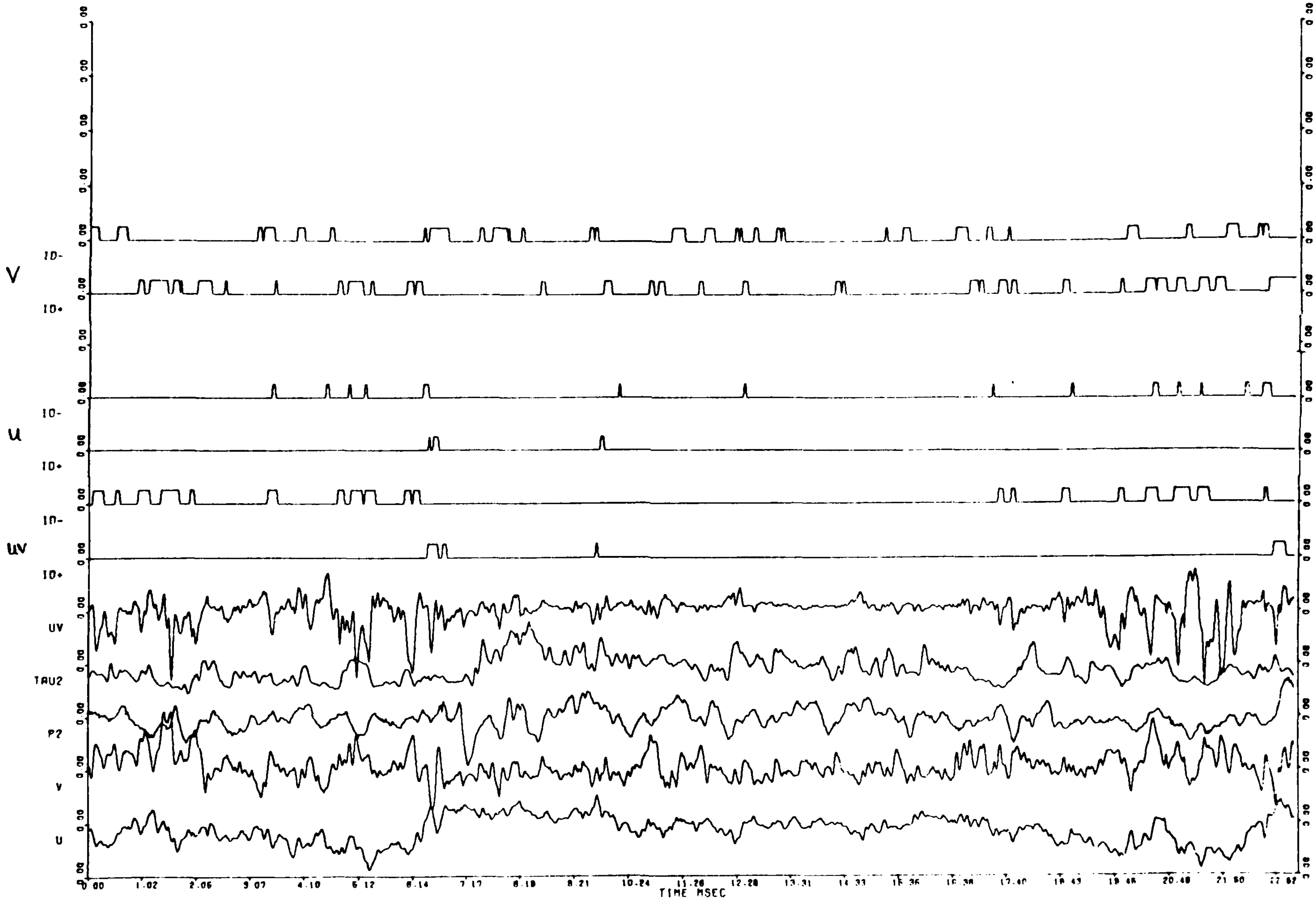
VORTICITY ARRAY: 31*31 AUG 82 Y/DELTA 0.114

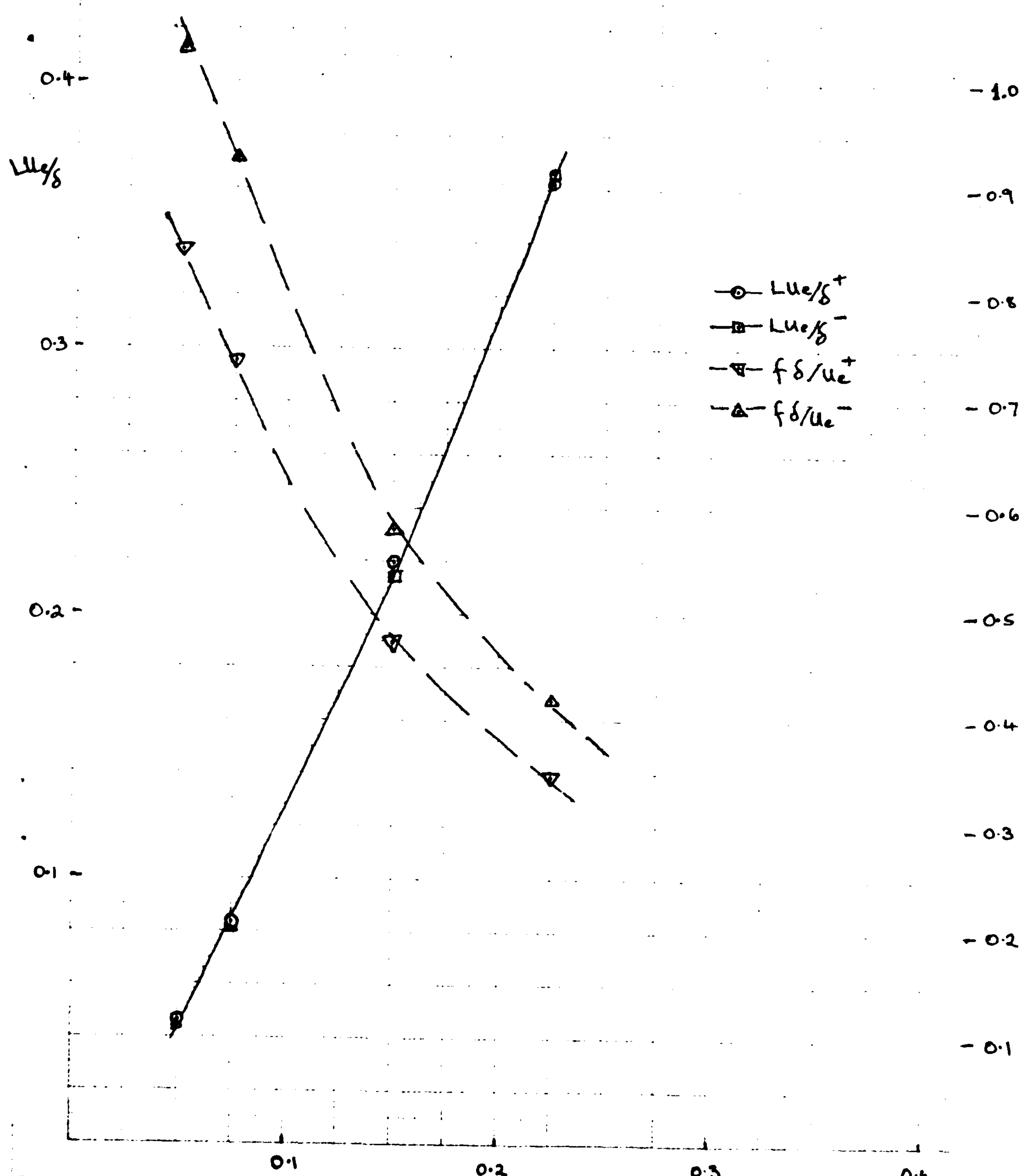
TAPE MISRUN UVP1

1.00617 INCH= 1.02 MSEC

50 POINTS PER INCH

RECORDS900 TO 905





0.4
0.3
0.2
0.1
LUe/δ
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
LUe/δ +
LUe/δ −
fδ/Ue +
fδ/Ue −
0.1
0.2
0.3
0.4

END

FILMED

DTIC